High Frequency GaAs Nano-Optomechanical Disk Resonator

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Optomechanical coupling between a mechanical oscillator and light trapped in a cavity increases when the coupling takes place in a reduced volume. Here we demonstrate a GaAs semiconductor optomechanical disk system where both optical and mechanical energy can be confined in a subwavelength scale interaction volume. We observe a giant optomechanical coupling rate up to 100 GHz/nm involving picogram mass mechanical modes with a frequency between 100 MHz and 1 GHz. The mechanical modes are singled-out measuring their dispersion as a function of disk geometry. Their Brownian motion is optically resolved with a sensitivity of 10^{-17} m/$\sqrt{\text{Hz}}$ at room temperature and pressure, approaching the quantum limit imprecision.

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Optomechanical systems generally consist of a mesoscopic mechanical oscillator interacting with light trapped in a cavity. These systems have attracted a growing interest since the first experimental evidence that cavity light can be used to optically self-cool the oscillator towards its quantum regime. They are now studied in an increasing number of geometries and compositions, with the common purpose of coupling photons and phonons in a controlled way [1–3]. High-frequency nanomechanical oscillators are usually welcome in optomechanics applications, to ease the access to the quantum regime or to develop high-speed sensing systems [4]. But because the typically subwavelength size of these oscillators often implies a weak interaction with light, they need to be inserted in the core of a cavity mode to enhance the optical-mechanical interaction [5]. The typical optomechanical coupling obtained using this approach is of 50 MHz/nm for visible photons [6,7] or 50 kHz/nm in the microwave range [8]. A coupling enhancement can be obtained by further confining mechanical and optical modes in a small interaction volume, as recently achieved in nanopatterned photonic crystals [9]. However, these structures are complex to design and fabricate, and being based on silicon technology, they do not allow the insertion of an optically active medium. This precludes exploring novel situations where a (quantum) mechanical oscillator would be coupled to a (quantum) photon emitter embedded in the host material [10]. In this Letter we present a gallium arsenide (GaAs) nano-optomechanical disk resonator, a system at the crossroads with III-V semiconductor nanophotonics. This resonator combines the assets of both nanoscale mechanical systems [high frequency and low mass in the picogram (pg) range] and semiconductor optical microcavities, with optical quality factor above 10^5. The high refractive index of GaAs enables storing light in a submicron mode-volume whispering gallery mode (WGM) of the disk, where it couples to high frequency (up to the GHz) vibrational modes of the structure. Thanks to the miniature optical-mechanical interaction volume, the coupling reaches 100 GHz/nm, providing nearly quantum-limited optical detection of vibrations. Besides offering high-frequency mechanical oscillators with an ultrasensitive optical readout, GaAs nano-optomechanical resonators are naturally suited for integration in geometry of arrays on a chip and for interfacing with single emitters in form of InGaAs quantum dots [11].

A whispering gallery disk structure is both an optical cavity and a mechanical oscillator. The radial breathing of the structure couples naturally to photons stored in the gallery mode, by modulating the effective optical length of the cavity. The related optomechanical coupling factor $g_{\text{om}} = (d\omega/d\alpha)$ accounts for the differential dependence of the cavity angular eigenfrequency ω on the mechanical displacement α, and enters the quantum description of the system coupled through radiation pressure $H_c = \hbar g_{\text{om}}(\hat{a}^+\hat{a})\alpha$, where $\hat{a}(\hat{a}^+)$ is the optical annihilation (creation) operator and α the mechanical degree of freedom. A large value of g_{om} is required for efficiently turning mechanical information into optical information and vice versa, and is hence beneficial to most applications in optomechanics. As we will see below, a miniature disk can sustain a very large value of g_{om}.

The WGM problem can be treated solving the Helmholtz equation in a cylinder of height h and radius R [12]. Provided that h is sufficiently larger than λ/n (thick disk limit) the effective index method can be employed to separate vertical (along cylinder axis) and horizontal dependence of the electromagnetic field F ($F = E$ or H). Using the rotational invariance, F is decomposed $F = \Psi(\rho)\Theta(\theta)G(z)$ with $\Theta(\theta) = e^{\text{i}m\theta}$. E.g., for the TM modes of azimuthal number m, the dispersion relation imposed by continuity of tangential E and H at the disk interface reads

$n_\zeta[\dot{J}_m(kn_\zeta R)/J_m(kn_\zeta R)] - \dot{H}_m^{(2)}(kn_\zeta R)/H_m^{(2)}(kn_\zeta R) = 0$, where n_ζ is the effective index of the slab of thickness h, J_m is the first-kind Bessel function of order m, ${H^{(2)}}_m$ is the second-kind Hankel function of order m, and $k = 2\pi/\lambda$. For a given h, this dispersion relation only depends on kR: if k_0 is a solution to this equation for a radius R_0, the solution k for radius R is given by $k = k_0R_0/R$. Thus in the limit of a thick disk, $d\omega/dR = -\omega/R$ is the exact optomechanical coupling factor g_{om} for a pure radial displacement dR. Thanks to a large refractive index, GaAs disks with radius as small as 1 μm can sustain high quality factor (Q) optical WGMs in the near infrared [13–15]. According to the formula $g_{\text{om}} = -\omega/R$, g_{om} values are expected to rise up to the THz/nm range on such disks.

Our GaAs disks are fabricated from an epitaxial wafer using e-beam lithography and wet etching [14]. The typical disk size is 5 μm in diameter and 200 nm in thickness, as seen in Fig. 1(a). Near-field experiments on a single disk are performed employing a microlooped optical fiber taper evanescent coupling technique at a wavelength of 1.55 μm [16,17], and using a balanced photodetector to remove the contribution of laser excess noise in the measurement [Fig. 1(b)]. When tuning the laser wavelength to a flank of the disk optical resonance [inset of Fig. 2(a)], the disk vibration modulates the optical transmission T of the fiber and the setup performs optical vibrational spectroscopy of the disk. At the inflection point of the flank and for a small displacement $\Delta\alpha$, we have $T(\Delta\alpha) - T(0) = (dT/d\omega)(d\omega/d\alpha)\Delta\alpha = [(3\sqrt{3})/4]\Delta T(Q/\omega)g_{\text{om}}\Delta\alpha$ [18], where $\Delta T = 1 - T_{\text{on}}$ is the contrast of the optical WGM resonance, T_{on} the on-resonance transmission, and Q the loaded optical quality factor, which is typically 10^5 in our experiments. ΔT and Q being measured quantities, the calibration of a vibrational measurement directly gives the optomechanical coupling factor g_{om}.

Figure 2 shows vibrational optical noise spectra obtained on selected disks at room temperature and pressure. Several mechanical resonances are observed with amplitude up to 20 dB over the noise floor. A striking feature is the high frequency of these resonances, from 100 MHz to 1 GHz [19]. This results from the small size of the disks, which also induces small motional masses (see also Table I). The mechanical Q factors span from a few tens to a few 10^3. Figure 2(d) shows a mechanical resonance at 858.9 MHz with $Q = 862$. This corresponds to a frequency-Q product of 0.7×10^{12}, approaching best reported values in the 10^{13} range [20] and obtained here in ambient conditions. Note that high purity crystalline GaAs mechanical oscillators should be free of mechanical losses affecting amorphous glasses at low temperature [21]. A GaAs micromechanical oscillator with Q factor above 10^5 has already been reported at low temperature [22].

Figure 2(b) displays a measurement of the disk Brownian motion at 300 K, showing a sensitivity of 2×10^{-17} m/$\sqrt{\text{Hz}}$. The calibration is obtained here using equipartition of energy for the Brownian motion amplitude [18] but it can also be obtained from an independent estimation of g_{om}, as detailed below.

The formula $g_{\text{om}} = -\omega/R$ is expected to be no longer valid if the mechanical mode has a nonradial component (out-of-plane motion) or in case the effective index approach does not hold anymore. The latter occurs if the disk is too thin ($< \lambda/n$) or if it is not a perfect cylinder. With a 200 nm thickness, we expect our GaAs disk resonators to deviate from $g_{\text{om}} = -\omega/R$. The general problem of how an optical resonator eigenfrequency ω depends on the deformation α of the resonator can be solved by a perturbative treatment of Maxwell's equations [23]. A convenient approach is to represent the resonator deformation by the displacement α of a chosen point of the resonator having maximum displacement amplitude. If the normalized displacement profile is known, α suffices to represent the complete resonator deformation field. With this approach g_{om} is expressed as the integral of

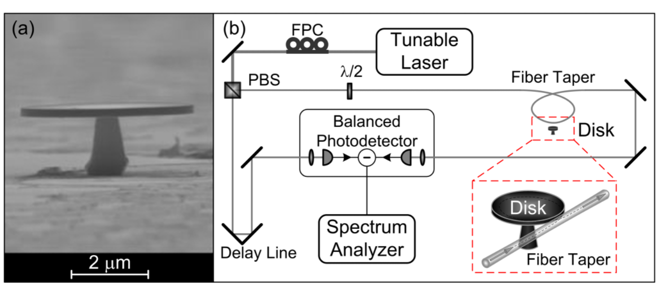

FIG. 1 (color online). Optomechanical study of a GaAs disk. (a) Scanning electron microscope (SEM) view of a GaAs disk (4.5 μm diameter and 200 nm thickness) suspended on an AlGaAs pedestal. (b) Schematics of the near-field optomechanical spectroscopy experiment. FPC stands for fiber polarization control, PBS for polarization beam splitter.

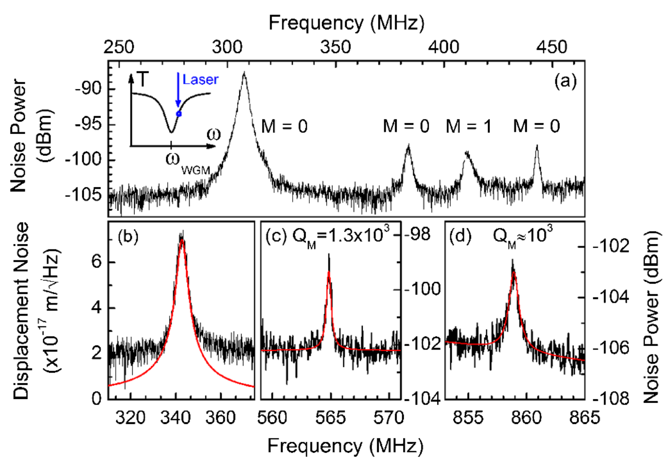

FIG. 2 (color online). Selected vibrational spectra of GaAs nano-optomechanical disks. (a) Optically measured motional noise spectrum of a disk of radius 5.6 μm and thickness 200 nm. (b) Calibrated displacement noise resonance of a disk of radius 4.5 μm, showing a sensitivity of 2×10^{-17} m/$\sqrt{\text{Hz}}$. (c),(d) High-frequency mechanical resonances of a disk of radius 3.6 μm in the 500 MHz–1 GHz band.

an optomechanical function over the rigid resonator boundaries:

$$g_{\rm om} = \frac{\omega}{4}\int(\mathbf{q}.\mathbf{n})[\Delta\varepsilon|\mathbf{e}_{\parallel}|^2 - \Delta(\varepsilon^{-1})|\mathbf{d}_{\perp}|^2]dA. \quad (1)$$

In this expression ω is the rigid resonator eigenfrequency, $\mathbf{q}$ is the normalized displacement profile vector such that $\max|\mathbf{q}(r)| = 1$, $\mathbf{n}$ the normal unit vector on the boundary, $\Delta\varepsilon = \varepsilon - 1$ with ε the dielectric constant of the resonator material, $\Delta(\varepsilon^{-1}) = \varepsilon^{-1} - 1$, $\mathbf{e}$ is the electric complex field vector normalized such that $\frac{1}{2}\int\varepsilon|\mathbf{e}|^2dV = 1$, and $\mathbf{d} = \varepsilon\mathbf{e}$ [9]. Importantly Eq. (1) shows that $g_{\rm om}$ depends both on the electromagnetic and mechanical mode under consideration, which in a GaAs disk are identified as explained now.

The WGM identification is carried out performing broadband optical spectroscopy of the disk to reveal a sequence of WGM resonances of varying linewidth and wavelength spacing. This sequence is compared to that obtained from numerical simulations [24], with a generally excellent overlap that imposes a unique radial-azimuthal label (p, m) to each optical resonance [17].

The identification of mechanical modes appearing in the measurement is more involved. Indeed, their frequencies depend on the exact geometry and composition of the disk and AlGaAs pedestal, and on the possible presence of residual stress in the material after etching. Here we identify each mechanical mode by studying its dispersion line as a function of the disk size, using for that purpose disks of different size but on the same sample, hence made out of the same material and resulting from the same fabrication process. Typically, for a disk of diameter 4.5 μm, the pedestal large and small diameters are 1 and 0.6 μm [Fig. 1(a)]. The disk thickness and pedestal height are controlled during epitaxial growth. The other geometrical parameters are measured with a precision of ±50 nm in a SEM and serve as input for numerical simulations, where we treat the material as isotropic and use elastic parameters at 300 K for GaAs (Young's modulus $E = 85.9$ GPa, Poisson ratio $\sigma = 0.31$, and density 5.316 g.cm^{-3}) and for $Al_{0.8}Ga_{0.2}As$ ($E = 83.86$ GPa, $\sigma = 0.39$, and density 4.072 g.cm^{-3}). These simulations provide us for each disk with a series of mechanical modes that can be named using radial and azimuthal numbers P and M. The displacement profile of a given mode can be factorized in the form $q(\rho, \theta, z) = \cos(M\theta) \times f_P(\rho, z)$ as a result of the rotational symmetry of the disk.

Figure 3 shows measurements performed on disks of radius varying between 3 and 6 μm. The shadowed guides to the eyes are obtained from simulations and displayed with a thickness of ±30 MHz corresponding to the uncertainty concerning the disk geometry. Figure 3 allows identifying the prominent mechanical resonances in the spectrum as having $M = 0$ and $M = 1$ azimuthal numbers (modes A, C and D of Fig. 3 correspond to $M = 0$ and mode B to $M = 1$). This identification is further confirmed by looking at the related optomechanical coupling. As a consequence of the disk rotational symmetry, the integral of Eq. (1) contains an azimuthal prefactor of the form $\int_{\theta=0}^{2\pi}\cos(M\theta)\cos^2(m\theta)d\theta = \frac{1}{2}\delta_{M,0} + \frac{1}{4}[\delta_{M+2m,0} + \delta_{M-2m,0}]$, where m (M) is the azimuthal number of the optical (mechanical) mode under consideration. This prefactor shows that the largest optomechanical coupling $g_{\rm om}$ is obtained for the mechanical azimuthal number $M = 0$. This is confirmed by our measurement where dominating resonances in the spectra always correspond to $M = 0$ modes.

In case of interest $m > 1$ and $\delta_{M+2m,0} = 0$. Apart from $M = 0$, the only case of nonzero optomechanical coupling is thus expected for $M = 2m$. In WGMs investigated here, m goes from 30 to 50. Mechanical modes with $M = 2m$ are hence of very high order and practically not visible in the spectra with the current sensitivity. In contrast, we observe mechanical modes with small azimuthal numbers ($M = 1, 2 \ldots$). Even though their weight in the spectrum remains small, their presence shows that the rotational symmetry of the disk and the above selection rules are only approximate.

Once both optical and mechanical modes are singled out in the measurement, the optomechanical coupling $g_{\rm om}$ is computed for each optical-mechanical combination using Eq. (1). The mechanical resonance shown in Fig. 2(b) corresponds, for example, to the $M = 0$ mode labeled A in Fig. 3. The optical resonance used in Fig. 2(b) has been identified to be the WGM ($p = 3$, $m = 33$). A numerically "simulated" value $g_{\rm om}{}^s$ of the coupling between these two modes is computed to be $g_{\rm om}{}^s = 61$ GHz/nm. But the effective mass of the mechanical mode also leads the Brownian motion amplitude by the equipartition theorem $m_{\rm eff}\omega^2\langle\Delta\alpha^2\rangle = k_BT$. Our measurements are performed at 300 K and the magnitude of the thermo-optic shift of the WGM resonance [25] indicates that heating induces

TABLE I. Optical-mechanical resonances of 3 GaAs disks, experimental (superscript e) and simulated (superscript s).

$R_{\rm disk}$ (μm)	λ_O (nm) (p, m)	Optical Q	$f_M{}^e$ (MHz)	$f_M{}^s$ (MHz)	$m_{\rm eff}{}^s$ (pg)	$g_{\rm om}{}^e$ (GHz/nm)	$g_{\rm om}{}^s$(GHz/nm)	Mechanical Q
4.5 ± 0.1	1551.7	1.0×10^5	343	339	21.2	71	61	66
	(3,33)		397	380	21.2	65	76	38
4.6 ± 0.1	1535.2	9.5×10^4	336	337	22.1	95	65	120
	(3,34)		395	380	20.9	60	72	66
5.6 ± 0.1	1513.9	5.9×10^4	308	326	36	132	78	73
	(3,45)		383.5	373	22.4	41	35	114

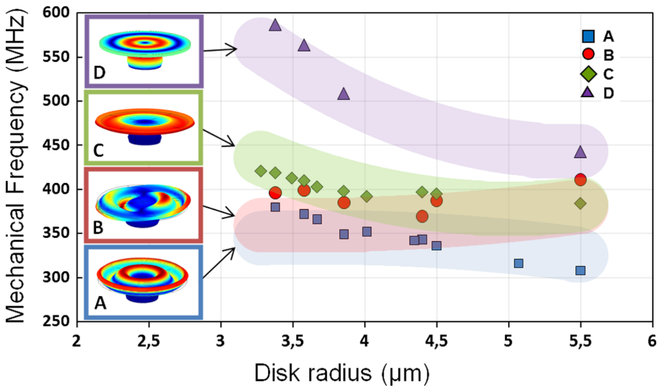

FIG. 3 (color online). Dispersion lines of GaAs disk mechanical modes measured vs disk radius. Thickness is 200 nm. Data points were acquired on different disks of the same sample. Transparent "guide to the eyes" bands correspond to numerical simulations with an error bar represented by their thickness.

negligible modification of the thermal motion amplitude. The Brownian motion can then also be used to calibrate the measurement and extract in a second independent manner an "experimental" value $g_{om}{}^{e}$ of the optomechanical coupling. $g_{om}{}^{e}$ and $g_{om}{}^{s}$ values are in reasonable agreement.

Table I contains the parameters relating to optical-mechanical resonances observed on 3 distinct disks. The effective masses are typically around 10 pg, with optomechanical coupling spanning from 30 to 150 GHz/nm. Combined with an optical Q factor in the 10^5 range, this leads to a typical displacement sensitivity of 10^{-17} m/$\sqrt{\text{Hz}}$. This is only a factor 100 above the standard quantum limit imprecision and is obtained here at room temperature and ambient pressure. This sensitivity compares favorably with other systems considering the nanoscale dimensions of the GaAs mechanical system under consideration and the high mechanical frequencies at play. Previous displacement sensitivities on MHz nanomechanical oscillators are of 10^{-16} m/$\sqrt{\text{Hz}}$ obtained with a single electron transistor at mK temperature [26], 10^{-15} m/$\sqrt{\text{Hz}}$ using a rf stripline cavity at mK temperature [8] and 10^{-15} m/$\sqrt{\text{Hz}}$ reachable using a high finesse fiber-cavity or a silica toroid as a mechanical-optical transducer [6,7]. A sensitivity in the 10^{-17} m/$\sqrt{\text{Hz}}$ range was recently reported in optomechanical crystals [9].

This sensitivity makes semiconductor disk resonators promising candidates to study quantum limits in optomechanics. For example, a GHz mechanical mode of a GaAs disk would have a mean thermal occupation number of only 35 at 1 K. Cavity self-cooling of such disk oscillator by a factor as low as 35 would allow it to enter the quantum regime, with the peculiar advantage that it would be available on a integrable optical platform. Besides the envisioned cavity-mediated coupling [27] of this quantum mechanical oscillator to an artificial atom (InAs quantum dot) for coherent control experiments, the GaAs-based optomechanical system presented here lends itself to the engineering of its optical and piezoelectrical properties through doping and the design of an embedded active medium. These original features should allow exploring novel architectures, at the frontier of III-V nanophotonics and optomechanics in the quantum regime.

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