Ground state cooling of a quantum electromechanical system with a silicon nitride membrane in a 3D loop-gap cavity

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Abstract

Cavity electro-(opto-)mechanics gives us a quantum tool to access mechanical modes in a massive object. Here we develop a quantum electromechanical system in which a vibrational mode of a SiN membrane are coupled to a three-dimensional loop-gap superconducting microwave cavity. The tight confinement of the electric field across a mechanically compliant narrow-gap capacitor realizes the quantum strong coupling regime under a red-sideband pump field and the quantum ground state cooling of the mechanical mode. We also demonstrate strong coupling between two mechanical modes, which is induced by two-tone parametric drives and mediated by a virtual photon in the cavity.

1. Introduction

Application of optical techniques, such as laser cooling and trapping, to the control of a massive object has gained much interest recently. They lead the progress in the control of the mechanical motions in the quantum regime. Moreover, the technical advancement in the micro/nanofabrications as well as material engineering enables construction of mechanical oscillators with a high quality factor in varieties of designs and forms. Cavity cooling of a mechanical oscillator, coupled to an electromagnetic resonator, down to the mechanical ground state was demonstrated through the radiation pressure both in the microwave and optical regimes [1–3]. Observation of radiation-pressure shot noise [4, 5], quantum nondemolition measurement and squeezing of a mechanical mode [6, 7], and bi-directional coherent transduction between microwave and optical photons [8, 9], were reported using various types of mechanical oscillators. In the microwave domain, it is of great interest to pursue coupling of a mechanical oscillator with a superconducting qubit to enhance its utility as a hybrid quantum system. Coherent coupling of a qubit with a bulk-mode phonon in a mechanical oscillator [10–12] as well as with a traveling phonon using a surface acoustic wave [13] were observed.

We report the development of an electromechanical system using a silicon–nitride membrane and a 3D loop-gap cavity. The 3D loop-gap cavity is constructed with the gap and the loop structure to sustain the electric and the magnetic field, respectively. This type of the microwave cavity is, for example, used for the detection of the electron spin resonance according to its strong confinement of the fields. Here, we construct the 3D loop-gap cavity with the mechanically compliant capacitor, which is galvanically contacted to the loop structure. Compared to the previously demonstrated electromechanical system using a 3D cavity [14], the galvanic contacts of the circuit provide the 3D loop-gap cavity geometry which avoids any serial capacitance: the presence of the parasitic serial capacitance decreases the participation ratio of the small-gap mechanical capacitor and made the coupling strength small in [14]. Additionally, in our 3D loop-gap cavity with the small-gap mechanical capacitance, the microwave electric field confined in the extremely small volume enhances the radiation pressure and the coupling strength is over one order of magnitude larger than that in the previous work. This enables the system to reach the so-called quantum strong coupling regime, where the coupling strength $G$
exceeds the quantum state diffusion rate $\Gamma_{\text{quant}} = n_{\text{th}} \Gamma_m$ due to the warm environment [15]. Here, $n_{\text{th}} = k_B T_{\text{bath}} / \hbar \omega_m$ is the thermal phonon occupation number at the reservoir temperature $T_{\text{bath}}, k_B$ is Boltzmann constant, and $\omega_m$ and $\Gamma_m$ are the eigenfrequency and the decay rate of the mechanical oscillator mode, respectively. The quantum strong coupling leads the ground state cooling of the mechanical mode: the minimum occupation number of the mechanical mode is less than 1. We also demonstrate tunable strong electromechanical coupling between two mechanical modes [16–21]. The coupling between mechanical modes can further enrich their utility in the quantum information processing and in the exploration of the fundamental physics via entanglement between mechanical modes [22, 23].

2. Device overview

Our electromechanical system consists of a 3D aluminum cavity and a capacitor-circuit chip as shown in figure 1(a). The capacitor circuit is constructed with an Al pad on a Si$_3$N$_4$ membrane chip and two electrodes on a bottom Si chip (figure 1(b)). The 50 nm-thick membrane is made of stoichiometric Si$_3$N$_4$ and supported with a Si frame. A pair of parallel-plate capacitors are formed by placing the membrane chip on the bottom chip.
The gap between the pad on the membrane and the electrodes on the bottom chip is approximately 300 nm, defined by the height of four pillars fabricated on the bottom chip.

### 2.1. Chip fabrication

Figure 1(d) shows the bottom Si chip and its fabrication process. All the aluminum circuits and structures are made by Al films evaporated and patterned with photo-lithography with S1805 photo-resist followed by wet-etching with TMAH etchant. First, 300 nm-tall Al pillars are formed on a Si substrate ($\rho > 10$ kΩ cm). Then, 100 nm-thick electrodes are evaporated and patterned with photo-lithography and wet-etching. The Si substrate surrounding the circuit is recessed by a deep reactive ion etching (Deep RIE). This design prevents small dust particles from affecting the separation between the membrane and the bottom chip. The depth of the etching is approximately 100 μm. The Si$_3$N$_4$ membrane is purchased from Norcada Inc. It is made of stoichiometric high-tension Si$_3$N$_4$ and spans on a Si frame with a square window of 500 × 500 μm. A 30 nm-thick Al pad is formed on the 50 nm-thick membrane. Figure 1(d) shows the flip-chip placement and adhesion procedure. We clean the surface of the bottom chip thoroughly and flip the membrane chip onto the bottom chip. The membrane chip is pressed against the pillars with spring-loaded pins and is glued with epoxy (Stycast 1285). As shown in figure 1(c) the interference effect between the reflected light from the top and the bottom electrodes varies the apparent color of the electrode at the overlapping region. The color depends on the distance between the electrodes, which we use for a qualitative check of the gap formation.

### 2.2. Cavity construction

Figure 1(e) indicates the photograph showing the construction of the 3D loop-gap cavity. The capacitor-circuit chip is loaded inside the 3D cavity to form a loop-gap cavity coupled with the mechanical motion of the membrane. The electrodes on the chip are galvanically connected to the cavity wall using an indium foil. In this configuration, the electric field is concentrated in the narrow gap capacitor, giving rise to the strong electromechanical coupling.

### 2.3. Galvanic coupling

One of the key features in our device is the galvanic connection of the mechanically compliant capacitor to the 3D cavity, which enhances the electromechanical coupling by mitigating the effect of the parasitic capacitance. To understand it, we compare two circuit designs whose equivalent circuits are shown in figure 2. In order to achieve a strong electromechanical coupling, it is generally important to have a narrow-gap capacitor $C_m$, such that a small displacement $x$ will cause a large variation in the capacitor to modify the resonance frequency of the entire LC resonator. The antenna coupling in figure 2(a), however, introduces parasitic series capacitance $C_c$, much smaller than $C_m$. This diminishes the variation of the total capacitance $C$ due to the displacement of the membrane as

$$
\delta C = \frac{C_c^2}{(C_c + 2C_m)^2} \frac{\partial C_m}{\partial x} \delta x \approx \left( \frac{C_c}{2C_m} \right)^2 \frac{\partial C_m}{\partial x} \delta x
$$

(1)

for $C_c \ll C_m$, leading to a small electromechanical coupling. In fact, in this setup, a larger mechanical capacitance will even hurt the system. It can easily be seen that a use of narrower gapped mechanical capacitor does not further enhance the coupling since that will lower the participation ratio. The circuit design with the

Figure 2. Comparison of the circuit designs. (a) Capacitive coupling of the 3D cavity. (b) Galvanic coupling of the 3D cavity. The electromechanical coupling $\partial C/\partial x$ in the latter case is larger than that in the former (see the details in the main text).
galvanically connected mechanical capacitor (figure 2(b)) solves the issue by introducing the idea of a loop-gap cavity, where the electric field is localized to the small mechanical capacitor gap, fully utilizing the mechanical variation of the capacitor. The variation of the total capacitance now reads
\[ \delta C = \frac{\partial C_m}{\partial x} \delta x. \]

3. Measurement setup

The 3D cavity is placed inside a dilution refrigerator for the microwave spectroscopic measurements. Figure 3 illustrates the microwave measurement setup. The base temperature of the fridge is 10 mK and the pressure of the sample region is below \(10^{-4}\) Torr from the cryo pumping. Attenuators are mounted on the input coaxial cable at each plate of the fridge to prevent the thermal noise from entering the cavity. The total attenuation through the input line is 50.3 dB at 5.4 GHz. For the output line, an isolator and a circulator protect the cavity from the thermal noise and the amplifier noise. The signal is amplified by the two low-noise amplifiers at 4 K (gain: 34.3 dB at 5.4 GHz) and room temperature (gain: 30.4 dB at 5.4 GHz). We use a vector network analyzer to observe the reflection coefficient \(S_{11}\) of the electromechanical system. We combine up to three microwave oscillators through a series of directional couplers for the experiment of the tunable intermodal mechanical coupling.

4. System diagnosis

4.1. Device parameters

The empty 3D cavity has the lowest-frequency mode at 16.7 GHz, which is lowered to \(\omega_0 / 2\pi = 5.343\) GHz when the capacitor-circuit chip is loaded (figure 3(a)). The oscillation of the membrane modulates the parallel-plate capacitances and thus the cavity resonance frequency. The electromechanical coupling strength is inversely proportional to the parallel-plate gap distance. From the capacitor geometry and the cavity frequency, we...
estimate the single-photon electromechanical coupling strength of $g/2\pi = 7$ Hz for the fundamental mode. The internal quality factor of the cavity is 18 000 at a probe power corresponding to the single-photon level inside the cavity. At higher probe power, the quality factor reaches as high as 180 000, presumably due to the saturation effect of the two-level systems associated with the cavity [24]. Figure 3(b) shows the noise spectrum of the mechanical sideband. The vibration frequency and mechanical decay rate of the fundamental mode is found to be $\omega_0/2\pi = 764$ kHz and $\Gamma_m/2\pi = 1.0$ Hz, respectively. The decay rate is obtained from the ring-down measurement.

4.2. Temperature calibration
In order to obtain the phonon number in the fundamental mode, we measure the mechanical noise spectra at different dilution fridge temperature for the calibration. A weak probe field is used to avoid cooling of the membrane by the probe field as well as the direct heating of the system from the input microwave. We plot the normalized area of the noise spectrum as a function of the bath temperature $T_{bath}$ and use the data at higher temperatures to calibrate the phonon number $\langle n_m \rangle$ with respect to the area of the spectra. As shown in figure 4(c) the lowest phonon number down to 550 was observed without additional cooling.

5. Experiments and results
5.1. Electromechanical quantum strong coupling
The canonical Hamiltonian of the electromechanical system is written as

$$\hat{H} = \hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar \omega_1 \hat{b}_1^\dagger \hat{b}_1 + \hbar g_0 \hat{a}^\dagger \hat{a} (\hat{b}_1 + \hat{b}_1^\dagger),$$

(3)

where $\omega_c$ is the cavity resonant frequency, $\hat{a}^\dagger (\hat{a})$ is the annihilation (creation) operator of the microwave photon, and $\hat{b}_1 (\hat{b}_1^\dagger)$ is the annihilation (creation) operator of the phonon. When the pump microwave frequency $\omega_p$ is tuned at the phonon red-sideband ($\omega_p = \omega_m - \omega_1$), the linearized Hamiltonian under the rotating-wave approximation reads [25]

$$\hat{H} = \hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar \omega_1 \hat{b}_1^\dagger \hat{b}_1 + \hbar G_1(\alpha) (\hat{a} \hat{b}_1^\dagger + \hat{a}^\dagger \hat{b}_1),$$

(4)

where $G_1(\alpha) = g_0 \sqrt{\alpha}$ is the parametrically enhanced coupling where $\alpha$ is the microwave amplitude in the cavity.
We perform microwave spectroscopy of the cavity in the presence of the red-sideband pump field. The reflection spectra ($|S_{11}|^2$) of the probe field for various pump powers $P_p$ are shown in figure 4. At the lowest pump power, the spectrum presents a feature known as electromechanically induced transparency [26], showing a narrow transparent window within the broad cavity resonance. As the pump power is increased, the width of the window increases. When the parametrically enhanced coupling strength exceeds the cavity linewidth, the normal mode splitting is observed. Other sharp dips observed at high pump powers are due to the weak electromechanical coupling with higher-frequency membrane modes. In addition, we observe an intricate cavity frequency shift, which is presumed to be originated from the nonlinearity of the cavity itself.

Figure 5 shows the pump-power dependence of the electromechanical coupling $G_1$ and the cavity linewidth $\kappa$. The cavity linewidth weakly depends on the pump power and is the narrowest at the highest pump power. The electromechanical coupling increases proportionally to the square root of the drive power as expected. A figure of merit of such hybrid quantum systems is often evaluated with the cooperativity $C = 4G_1^2/\kappa\Gamma_1$. However, when the bath temperature is much higher than the single-phonon temperature $T_{ph} = h\omega_1/k_b$, it is more appropriate to evaluate the system with the quantum cooperativity $C_{quant}$ which expresses the strength of the electromechanical coupling with respect to the diffusion rate due to the thermal environment. Quantum controllability of the electromechanical system requires the condition $C_{quant} > 1$. The maximum quantum cooperativity obtained for our system is

$$C_{quant} = \frac{4G_1^2}{n_{th1}\Gamma_1} = 1750 \gg 1,$$

where $n_{th1} (\approx 550)$ is the thermal population of the membrane mode. Moreover, the electromechanical coupling strength is larger than the cavity linewidth and the mechanical decoherence rate in the thermal environment, meeting the condition for the strong coupling, $G_1 > \kappa, n_{th1}\Gamma_1$.

For fitting the cavity reflectivity spectrum in the presence of a mechanically induced transparency window, we use a function

$$f(\omega) = |a_1\exp(i\theta_1) + a_0[1 - \sqrt{\xi}\kappa g(\omega)][|^2,$$

where

$$g(\omega) = \frac{\sqrt{\xi}\kappa}{-i(\omega - \omega_c) + \kappa/2 + G_1^2/[1-i(\omega - \Delta_p) + \Gamma_1/2]},$$

$a_1$ and $\theta_1$ are respectively the amplitude and the phase of the stray microwave field caused by reflections at various microwave components along the measurement line, $\kappa$ the total linewidth of the cavity, $\xi = \kappa_{ex}/\kappa$ the ratio of the external coupling to the total linewidth of the cavity, $\omega_c$ the cavity resonant frequency, $\Delta_p = \omega_c - \omega_p - \omega_m$ the detuning of the electromechanical coupling, $\Gamma_1$ the linewidth of the fundamental mechanical mode, and $G_1$ the electromechanical coupling. The fitting parameters are $\{a_1, \theta_1, \kappa, \eta_1, \omega_c, G_1\}$, while fixing $\Gamma_1/2\pi$ at 1 Hz, which we obtained from the independent measurement.
5.2. Ground state cooling
We also perform cavity sideband cooling of the membrane oscillation. We pump the system with a red-detuned microwave and monitor the noise spectrum of the reflected pump field, from which the noise spectrum $S_x$ of the mechanical oscillation is calculated directly [1]. Figure 6 shows the mean phonon number of the membrane as a function of the pump amplitude. The minimum occupancy is obtained as $\langle n \rangle = 0.51 \pm 0.12$ at $P_p = -70 \text{ dBm}$, showing that the system is in the quantum regime. While the minimum phonon number expected from the quantum cooperativity in equation (5) is much smaller than 0.51, the cooling is limited by the heating of the cavity mode. With further increase of the pump amplitude, the microwave cavity mode gets populated, which also heats the mechanical mode. The occupancy of the cavity field $\langle n_c \rangle$ is calculated from the noise floor level of the microwave noise spectrum [14]. The phase noise of our oscillator is negligible at this power range.

5.3. Tunable intermodal mechanical coupling
The particular design of the Al pad on the membrane also allows strong electromechanical coupling of the cavity with other membrane modes. Figure 7(a) shows examples of simulated spatial modes of the membrane oscillations. The left panel shows the profile of the fundamental mode (mode 1) with $\omega_1/2\pi = 764 \text{ kHz}$, where the mode structure is little affected by the presence of the pad. On the other hand, the right panel shows the mode shape of a higher-frequency mode (mode 2) with the eigenfrequency of $\omega_2/2\pi = 2460 \text{ kHz}$. The Al pad breaks the symmetry of the mode and largely modifies the mode shape. Both of the mechanical modes have significant spatial overlap with the Al pad, resulting in strong coupling with the cavity mode. The decay rate of mode 2 is found to be less than $\Gamma_2/2\pi < 1 \text{ Hz}$ from a measurement using the electromechanically induced transparency (figure 7(b)). The measurement is limited by the bandwidth of the network analyzer.

These two mechanical modes can be coupled simultaneously to the microwave cavity mode with two drive fields. Figure 7(c) is an energy diagram illustrating the mechanical and the resonator modes as well as the microwave tones used for the interrogation of the intermechanical coupling. We drive the cavity with two tones at the frequencies $\omega_{11}$ and $\omega_{12}$, both off-resonant from the microwave cavity frequency $\omega_c$. Let us define the detunings $\delta_1 \equiv \omega_c - \omega_1 - \omega_{11}$ and $\delta_2 \equiv \omega_c - \omega_2 - \omega_{12}$. When the detunings are large enough, satisfying $\delta_1, \delta_2 > \kappa$, the microwave cavity mode can be adiabatically eliminated, leaving the two membrane modes parametrically coupled. At two-photon resonance $\delta_1 = \delta_2$, the interaction Hamiltonian between the two mechanical modes reads [16].
\[ \hat{H}_f = \eta (\hat{b}_1^\dagger \hat{b}_2 + \hat{b}_1 \hat{b}_2^\dagger), \]  

where \( \hat{b}_2 \) is the annihilation operator of mode 2, \( \eta = G_1 G_2 / \hbar \) is the coupling strength between mode 1 and 2, where \( G_1 \) and \( G_2 \) are the parametrically induced coupling strengths between the cavity mode and mode 1 and 2, respectively.

To observe a signature of the parametrically induced multimode coupling, we probe the shift of the fundamental mode via mechanically induced transparency, while sweeping the detuning of one of the drive fields (Figure 7(c)). Figure 7(d) shows the probe reflectance \( |S_{11}|^2 \) as a function of the drive detuning \( \delta_2 - \delta_1 \) and the probe detuning \( \Delta = \omega - \omega_p \). The white dots depict the cross section of the anticrossing at \( \delta_1 = \delta_2 \). The red curve is the numerical simulation. (e) Strength of the parametrically induced interaction \( \eta \) between the two mechanical modes in the membrane. We vary the drive powers and detuning \( \delta_1 \). The horizontal axis shows the calculated mechanical coupling \( G_1 G_2 / \hbar \). The number on each dot indicates the corresponding parameter set in Table S1. Dots are the experimentally obtained coupling strength between the two modes. The dashed line indicates \( \eta_{\text{cal}} = G_1 G_2 / \hbar \).
The obtained coupling is already in the strong coupling regime. However, the quantum cooperativity between the two mechanical modes \( C_{\text{quant}} = \frac{C}{\hbar \Omega_1 \Omega_2} \) is smaller than 1, and our system is not in the quantum strong coupling regime yet. The coupling strength is now limited by the maximum driving power.

In the cross section shown with white dots in figure 7(d), an asymmetry between the hybridized modes is observed. The asymmetry arises from the decoupling of one of the hybridized modes (upper peak in the figure) from the two drive fields: the three strong fields including the pump field also act as cooling fields for the mechanical modes, resulting in the broadened linewidths, while the upper hybridized mode is a dark mode for the two drive fields and is subject to less cooling. The red curve in figure 7(d) is the numerical simulation with parameters \( G_1/2\pi = 12 \, \text{kHz}, G_2/2\pi = 3.7 \, \text{kHz}, \delta_1/2\pi = 1200 \, \text{kHz}, G_3/2\pi = 0.6 \, \text{kHz} \) and \( \kappa/2\pi = 200 \, \text{kHz} \), where \( G_3 \) is the electromechanical coupling induced by the pump field.

The coupling strength can be tuned with the powers of driving fields. When the two drive fields are on resonance \( \delta_1 - \delta_2 = 0 \), the coupling strength between the two mechanical modes is given as \( \eta_{\text{cal}} = G_1 G_2/\delta_1 \), where \( G_i \) (\( i = 1, 2 \)) is the electromechanical coupling of mode \( i \) with the cavity mode and \( \delta_i \) is the detuning of the drive field \( i \). We measure \( G_i \) by the electromechanically induced transparency at each drive power. Table 1 shows the compiled data of the measured coupling strength \( \eta_{\text{exp}} \) between the two mechanical modes for various sets of \( G_1, G_2 \), and \( \delta_1 \). Figure 8(e) represents the coupling strength of these data. From these values of \( G_i \) and the intra-cavity photon number estimated from the input–output theory, we obtain the single photon coupling strength \( g_i/2\pi = 7.20 \, \text{Hz} \) and \( g_3/2\pi = 1.04 \, \text{Hz} \). The measured values of \( \eta_{\text{exp}} \) agree well with the theoretical values.

6. Conclusion

We demonstrated strong electromechanical coupling between a 3D loop-gap microwave cavity and a membrane mechanical oscillator. The quantum cooperativity of the electromechanical coupling reached more than a thousand under a strong drive field. The quantum ground state cooling was also achieved. As our system is constructed with a 3D microwave cavity, the nonlinearity of the cavity is significantly weaker than that of 2D systems, and the strong pump field can be applied for the ground state cooling and the precise measurement of the mechanical mode. Moreover, it can easily incorporate, e.g., a superconducting qubit, for realizing hybrid quantum systems capable of non-classical state manipulations and measurements. We also implemented a multimode quantum electromagnetic system by parametrically coupling two mechanical modes via the cavity mode with two microwave drive fields. Multiple mechanical modes in the quantum regime can be an extra resource in quantum electromechanical systems, e.g., for realizing quantum state preparation based on reservoir engineering [27].

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