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Piezoelectric control of coupled vibration in elastically coupled nanomechanical oscillators

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1. Introduction

In recent years, nanomechanical oscillators have been extensively used for a wide variety of applications, including sensors, actuators, and filters. Coupled nanomechanical oscillators are also getting a lot more attention lately because of their interesting physical phenomena [1-5]. For example, the vibrational mode localization, which is induced by the disorder of the eigenfrequencies in the coupled oscillators, can be used for high-sensitivity mass detections [2-4]. Coupled nonlinear oscillators that exhibit frequency entrainment are attracting attention as a tool for studying synchronization, which is found not only in mechanical systems but also in biological ones [5].

The vibration coupling in coupled oscillators depends on the eigenfrequency difference between the oscillators. Therefore, frequency tuning (detuning) is an important aspect for the study of dynamic behavior in coupled oscillators as well as for their practical applications. Frequency tuning in coupled nanomechanical oscillators has recently been demonstrated by using laser-induced photothermal stress [6,7]. However, the application of this optical method to coupled oscillator arrays is limited because it requires multiple laser optics. Thus, alternative methods should be used for the operation of coupled nanomechanical oscillators. Here, we demonstrate all-electric operation of coupled oscillators, i.e., electric actuation, detection, and frequency tuning, by using the piezoelectricity in compound semiconductors. With this method, we can achieve perfect vibration coupling as well as the control of coupled vibration.

2. Experimental

The coupled oscillators are two doubly clamped beams of 100-µm lengh, 34-µm width, and 0.8-µm thickness, which are elastically coupled with each other through an etched overhang [Fig. 1(a)]. Each beam consists of three compound semiconductor layers (undoped *i*-GaAs, Si-doped *n*-GaAs, and $Al_{0.25}Ga_{0.75}As$) and Cr/Au gates, which were formed by molecular beam epitaxy, photolithography, and electron beam deposition [Fig. 1(a)]. An ohmic contact to the conductive *n*-GaAs layer was made with sintered AuGeNi in the supporting region. The two beams are oriented along [110], while the crystal growth direction is [001] [Fig. 1(a)]. This orientation enables the use of piezoelectricity, i.e., the application of a vertical electric field via gate electrodes induces longitudinal stress, leading to a change in the tension of the beam [7,8]. DC voltage was applied to gate T1 (T2) to change the eigenfrequency of beam 1 (2) while the *n*-GaAs layer grounded [Fig. 1(b)]. The applicable voltage is between +0.5 and -5 V, which is limited by the breakdown voltage. Beam 1 (2) is actuated by applying 7 mV_{rms} AC voltage to gate A1 (A2) near the resonance frequency [Fig. 1(b)]. The electric field between the top gate and the *n*-GaAs layer induces modulated piezoelectric stress in $Al_{0.25}Ga_{0.75}As$, but not in *i*-GaAs. Therefore, the AC gate modulation results in the bending of the beam, enabling the mechanical resonance at the vibrational mode frequencies. Vibrations of beams 1 and 2 are simultaneously monitored by detecting voltage at gates D1 and D2, which is induced by the converse piezoelectric effect, with pre- and lock-in amplifiers [Fig. 1(b)]. The measurements were done in a vacuum (~10^{-7} Torr) at room temperature.

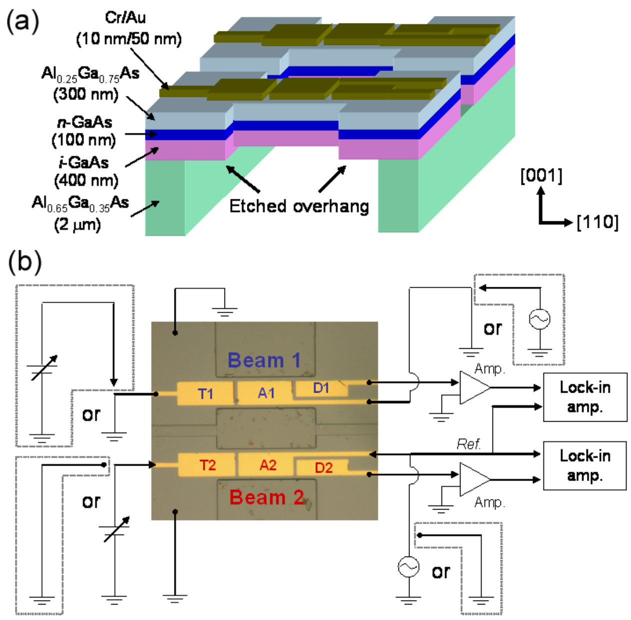

Fig. 1. (a) Schematic of the coupled oscillators. Two doubly clamped beams are elastically coupled via the etched overhang. (b) Optical micrograph of the sample and a schematic of the measurement setup.

3. Results and discussion

Figures 2(a) and (b) show the detuning voltage (V_{T2}) dependence of the mechanical resonance characteristics of beams 1 and 2, respectively, measured by actuating beam 1 via gate A1 while detecting voltage at gate D1 (V_{D1}) and gate D2 (V_{D2}) simultaneously. The two resonance peaks found in the figures correspond to the coupled two vibrational modes of the two beams. When no voltage is applied to gate T2 (V_{T2} = 0), the frequency of the two modes is 238.80 and 240.95 kHz, respectively. The higher mode frequency is reduced by applying negative voltage to gate T2. This is because the induced piezoelectric stress in the longitudinal beam direction reduces the tension of beam 2, leading to a decrease in the eigenfrequency [7]. This frequency change indicates the eigenfrequency of beam 2 was initially higher than that of beam 1 because of manufacturing errors. The rate of the piezoelectric frequency shift is Δf = -0.95 kHz/V. This frequency shift leads to the avoided crossing of the two modes, where the frequency difference is minimized at V_{T2} = -2.17 V [Figs. 2(a) and (b)]. This characteristic can be understood by considering the following theory: The equation of motion for coupled oscillators is given by

$$\begin{cases} m_1\ddot{z}_1 + m_1\gamma_1\dot{z}_1 + (k_1+k_c)z_1 - k_c z_2 = F\exp(i\omega t) \\ m_2\ddot{z}_2 + m_2\gamma_2\dot{z}_2 + (k_2+k_c)z_2 - k_c z_1 = 0, \end{cases} \qquad (1)$$

where z_n is the displacement of the n-th oscillator given by $z_n = A_n \exp i(\omega t + \phi_n)$, m_n the mass, γ_n the damping factor, k_n the spring constant, k_c the coupling constant, and F the external force. Equation (1) results in two eigenvalues and for $m_1 = m_2 = m$, for simplicity,

$$\omega^2 = \frac{k_1}{m}\left\{ \frac{1}{2}\left(1+\frac{k_2}{k_1}\right) + \frac{k_c}{k_1} \pm \frac{1}{2}\sqrt{\left(1-\frac{k_2}{k_1}\right)^2 + 4\left(\frac{k_c}{k_1}\right)^2} \right\} \qquad (2)$$

For the perfectly tuned condition $(k_1 = k_2 = k)$, the difference of the two eigenvalues is minimized but has a finite value depending on the coupling constant, i.e., $\omega_a^2 - \omega_s^2 = 2k_c/m$, where $\omega_s^2 = k/m$ and $\omega_a^2 = (k+2k_c)/m$. The ratio of z_1 to z_2 is 1 at ω_s and -1 at ω_a, i.e., the two modes correspond to symmetric and anti-symmetric vibration of the two oscillators at the perfect tuning point [6]. By detecting the phase information with the lock-in amplifiers, we can confirm that the two modes at V_{T2} = -2.17 V have the same phase for beam 1 but are π-phase different for beam 2. The experimentally obtained coupled mode frequencies shown in Figs. 2(a) and (b) are well fitted by Eq. (2). The strength of coupling is estimated to be $k_c = 1.5\times10^{-3}\, k$ ($k \cong 36\ N/m$).

4. Conclusions

We have demonstrated all-piezeelectric operation of coupled nanomechanical oscillators at room temperature. We will be able to use the piezoelectric control of coupled vibration for applications of coupled nanomechanical oscillators, such as highly sensitive sensors, as well as for the study of the dynamics in coupled systems.

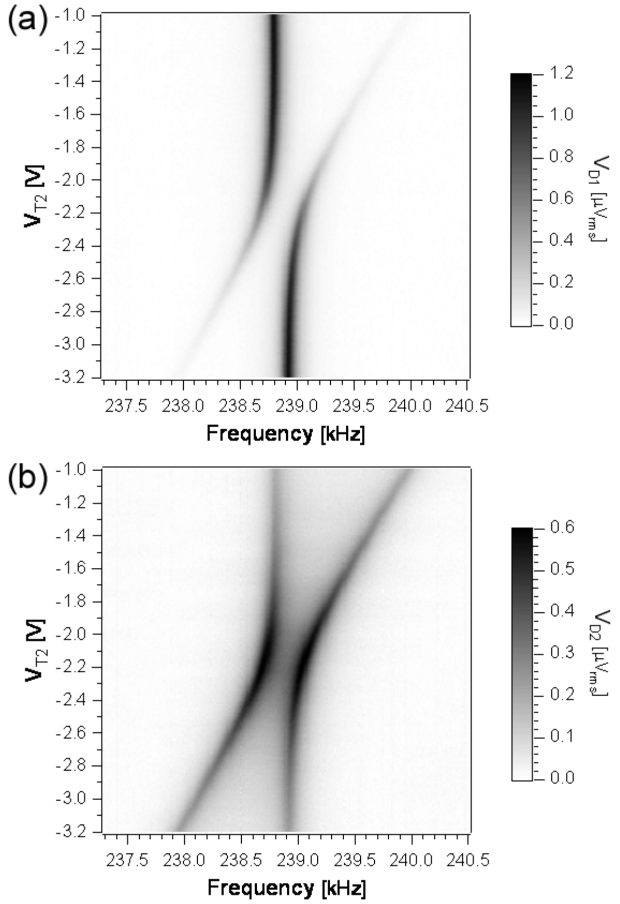

Fig. 2. Detuning voltage (V_{T2}) dependence of the mechanical resonance characteristics of beam 1 (a) and beam 2 (b) measured by actuating beam 1 via gate A1 while detecting voltage at gate D1 (V_{D1}) and gate D2 (V_{D2}) simultaneously.

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