Low temperature study of loss mechanisms of mechanical oscillators

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Abstract

In order to understand the loss mechanism of mechanical oscillators in micro-electromechanical systems, we have studied the temperature dependence of the quality factor Q of a high Q silicon mechanical oscillator from 0.4 K to 300 K. At temperatures above 70 K, the energy loss is principally caused by thermoelastic effect in the flexural components of the modes. Below 50 K, we find the improvements in vibration isolation guided by the finite element method do not significantly improve its Q. This indicates that some intrinsic loss mechanism may still be important even at low temperatures.

Keywords: mechanical oscillator, quality factor, micro-electromechanical system

1. Introduction

Achieving a high value of Q in mechanical oscillators has emerged as a key issue in various applications [1,2], particularly in micro-electromechanical systems (MEMS) [3–5]. This has attracted research interest in understanding the loss mechanisms in such systems [6,7]. In general, the energy loss of a mechanical oscillator includes two parts: external loss in which net energy in terms of sound waves flows out of the oscillator through attachments, and internal loss which involves various phonon scattering processes within the bulk and surfaces of the oscillator.

The external loss is an important limiting factor of Q in many oscillators made of properly chosen materials, and in practice it is difficult to separate the external loss from the internal ones. Therefore, a careful comparison of internal loss mechanism with theoretical predictions has not been made.

The double-paddle oscillators (DPO), fabricated with silicon nanofabrication technology, have achieved a Q of 5×10^7 at temperature below 10 K [8]. We have shown that the high Q is attributed to its excellent vibration isolation [9]. In this paper, we use the DPO as a platform to study the loss mechanism, and to try to improve their Q further.

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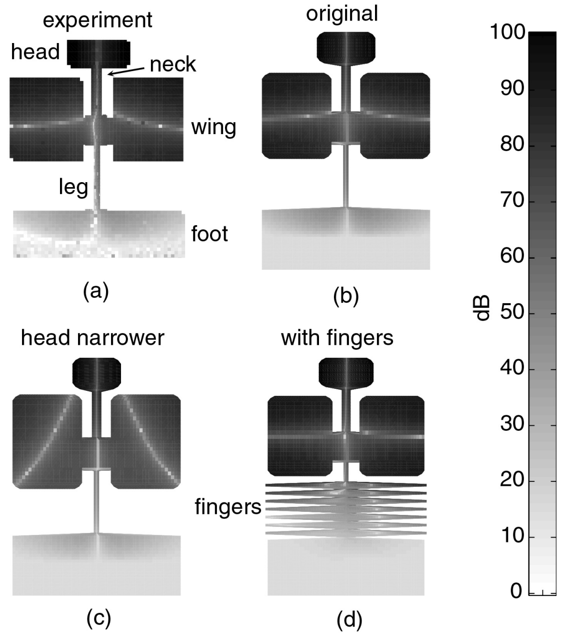

Fig. 1. Gray-scaled normal component of the amplitude of the surface velocity for the AS2 mode of the DPO. (a) shows original geometry, measured by the LDV. (b),(c), and (d) are all FEM calculations for geometries of original, with smaller head, and with fingers, respectively. Each picture is scaled to a common total kinetic energy. To distinguish the oscillator shape, 0 DB is offset. The improvements in vibration isolation from (b) to (d) are clearly visible from the reduction of amplitude on the foot.

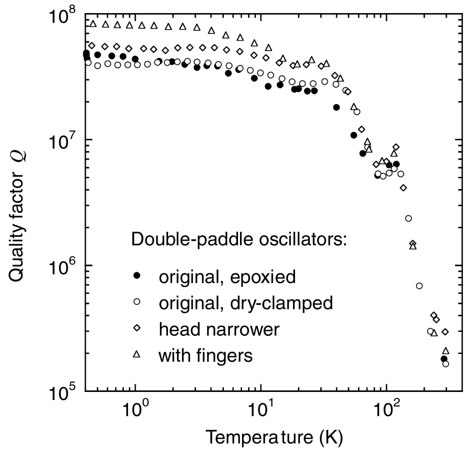

Fig. 2. Quality factor Q vs. temperature for the AS2 mode of the DPO. The data labeled as "original, epoxied" and "original, dry-clamped" correspond to the geometry shown in Fig. 1 (b), "head narrower" to (c). and "with fingers" to (d).

2. Measurements and results

The oscillator was made of 300 μm thick single-crystalline silicon wafer, with its long axis along the $\langle 110 \rangle$ orientation. We only discuss the 2nd anti-symmetric torsion (AS2) mode, which has the resonance at 5.5 KHz and has the highest Q among the 7 modes studied [10]. In this mode, the head and wings rotate out of phase with one another. Due to large inertia ratio between the head and wings, vibration transmitted through the leg, the source of loss to the external environment, nearly vanishes.

In [9], we reported laser Doppler vibrometry (LDV) measurements of the lowest 7 out-of-plane modes of the DPO and the corresponding finite element modeling [11]. The direct LDV measurements have enabled us to establish a detailed finite element method (FEM) predictive capability for the frequencies and mode shapes of the DPO. For the AS2 mode, we reproduce, from [9], the resulting velocity profile measured with LDV and the modal behavior predicted by FEM in Fig. 1 (a) and (b), respectively.

The temperature dependent Q is shown in Fig. 2, where the label "expoxied" refers to the mounting in that epoxy was used to glue the oscillator onto an Invar block. At low temperatures, the Q is orders of magnitude worse than the known phonon scattering mechanisms, i.e. phonon-phonon interaction and thermoelastic effect [12]. Therefore, the damping is presumably external, and is dependent on the oscillator mounting and the environment. However, modifying the mount by adding a heavy block of beryllium copper, known to have very little damping at low temperatures [13], or by inserting a lead foil between Invar block and cryostat, has no effect on the damping. Even replacing the epoxy by dry clamping has no effect (Fig. 2). The decrease of Q towards higher temperature can be explained by the thermoelastic effect in the flexural component of the vibration, which dominates the Q above 70 K [7].

In [9], we have shown that the square root of the kinetic energy in the foot relative to the total kinetic energy,

$$V_{z,\mathrm{ratio}} = \sqrt{\int_{\mathrm{foot}} |v_z|^2 dA \Big/ \int_{\mathrm{osc}} |v_z|^2 dA}, \qquad (1)$$

is empirically proportional to the external energy loss (the in-plane components are negligible). Two modifications of the DPO are shown in Fig. 1 (c) and (d) as the modal behavior predicted by FEM. The purpose of these designs is to minimize the external energy loss with better vibration isolation quantified by Eq. 1. As shown by the gray-scale in Fig. 1, the amplitude on the foot is lower in (c) and (d)than in (a) and (b). For the design shown in Fig. 1 (c), we narrow the width of the head, and enlarge the length of the wings. As a result, the motion of the wings is minimized and $V_{z,\mathrm{ratio}}$ is reduced by a factor of 2.3. As shown in Fig. 2, however, while the room temperature Q is improved by a factor of ≈ 1.7, no significant improvement is achieved at low temperatures. Even the reduction at room temperature is partially attributed to the reduction of flexural components in the AS2 mode.

For the design shown in Fig. 1 (d), we slightly increase the length of the leg to accommodate 7 fingers on each side of it. The fingers is designed to create a stop band at the resonance of the AS2 that reflects the sound waves, thus keeping the foot from vibration. As a result, the vibration amplitude diminishes gradually at the fingers, and very little is left on the foot (Fig. 1 (d)). The FEM calculation and LDV measurement show that $V_{z,\mathrm{ratio}}$ is reduced by a factor of 71 and 31, respectively, from the original design. Yet, the Q only increases by a factor of two at low temperatures (Fig. 2). The difference between the FEM and LDV results is attributed to the slight asymmetry of the real oscillator that induces a small portion of translational oscillation at the foot.

The experiments presented above raise the question whether we have reached the limit of vibration isolation and the Q can be considered as intrinsic. If so, the theories regarding the damping mechanisms that could be applied to single crystalline silicon [12] are inadequate in providing an explanation at temperatures below 10 K. At this point, we have to keep in mind that even if the loss is intrinsic, a contribution from the thin metal films on the silicon (500ÅAu and 30 ÅCr), used as conductive coating for capacitive drive and detection can not be ignored [14,15]. Experiments are underway to improve Q by minimizing the impact of metal films. A better low temperature Q (1×10^9) has been reported by McGuigan et al. [16] on a suspended silicon cylinder. Although their geometry is unapplicable to MEMS, it certainly encourages improvement efforts.

3. Conclusion

We have successfully improved the vibration isolation of a silicon mechanical oscillator with the help of the FEM tool. Eliminating the external loss opens up the opportunity to study the internal loss mechanisms and phonon processes associated with the material and the oscillator itself. The DPO provides an excellent platform to study the physics of MEMS oscillators.

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