Hybrid device for acoustic noise reduction and energy harvesting based on a silicon micro-perforated panel structure*

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A kind of hybrid device for acoustic noise reduction and vibration energy harvesting based on the silicon micro-perforated panel (MPP) resonant structure is investigated in the article. The critical parts of the device include MPP and energy harvesting membranes. They are all fabricated by means of silicon micro-electro-mechanical systems (MEMS) technology. The silicon MPP has dense and accurate micro-holes. This noise reduction structure has the advantages of wide band and higher absorption coefficients. The vibration energy harvesting part is formed by square piezoelectric membranes arranged in rows. ZnO material is used as it has a good compatibility with the fabrication process. The MPP, piezoelectric membranes, and metal bracket are assembled into a hybrid device with multifunctions. The device exhibits good performances of acoustic noise absorption and acoustic–electric conversion. Its maximum open circuit voltage achieves 69.41 mV.

Keywords: hybrid device, noise energy harvesting, acoustic noise reduction, silicon micro-perforated panel

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1. Introduction

Energy harvesting device research is the hot topic. It is because the wireless sensor nodes and other micro-systems in the internet of things, which do rely on the replaceable battery, need to collect power locally from the environment. Acoustic noise is common in the environment[1] and could be used to generate electricity. A device which is able to integrate the functions of noise reduction and energy generation would be meaningful. This technology would be promising to supply the power consumption (∼mW) of these micro-systems, so as to reduce the maintenance cost of the wireless micro-systems. The micro-perforated panel (MPP) resonant structure has good capability of noise reduction, while the piezoelectric thin film is able to convert the acoustic energy into electricity effectively. So a novel noise energy harvesting device based on the silicon MPP resonant structure and piezoelectric thin film is designed and fabricated by micro-electro-mechanical systems (MEMS) technology in this article, and the characteristics of the device are investigated thoroughly as well. The physical model of the device is given based on the theory of MPP and the acoustic–electric conversion. The relevant theories would be the guidelines to improve the performance of the device.

The MPP resonant structure has been widely used in the acoustic noise reduction field for its good noise absorption presentation. The characteristics of various MPP structures[2–4] with a paralleled multi-leaf,[5] a flexible panel[6] or an alterable cavity, etc. have been studied and presented in recent years. Most of the MPP structures mentioned above are manufactured by the traditional mechanical method. According to relative theory, MPP is able to realize high and wide band noise absorption when the density of the micro-perforators is high and the dimension of the perforators is small. There would be many difficulties when we still use the original method to fabricate this kind of MPP. MEMS technology is good at batch fabrication and micro-machining, thus it would be the appropriate method to form a better acoustic noise absorber.

Acoustic noise vibration in the MPP could be used to actuate the vibration energy conversion device for electricity generation. Many kinds of vibration energy harvesters have been reported, such as the cantilever beam,[7] the piezoelectric membrane,[8] nanowire arrays,[9,10] and the Helmholtz-cavity structure.[11,12] But all of them seldom have the multifunction of acoustic noise reduction and noise energy harvesting in the audible spectrum. The device introduced in the article is assembled by the silicon MPP, ZnO piezoelectric membranes array,[13–15] and a solid bracket. The average absorption coefficient of the device is above 0.7 in a bandwidth from 1500 Hz to 6000 Hz, and its maximum open circuit output voltage is about 70 mV.

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2. Theory

The basic theory of the MPP was put forward by Maa in 1975.[16–18] Its structure is depicted as the top panel in Fig. 1. And d, t, and b denote the diameter of the micro-perforator, the thickness of the panel, and the distance between the perforators, respectively. Suppose air density $\rho = 1.2$ kg/m^3, air dynamic viscosity $\eta = 1.789$ kg/ms, the sound speed $c = 340$ m/s in air. Let f be the resonant frequency (kHz), p the ratio of perforators' area to panel's area, and $Z_0 = \rho c$ the air impedance ratio. The simplified relative acoustic impedance proportion Z_r of MPP in the air could be expressed as

$$Z_r = r + j\omega \cdot m \tag{1}$$

with

$$\begin{aligned} &r = \frac{0.147}{d^2} \cdot \frac{t}{p} \cdot K_r, \\ &(\text{in which } K_r = \sqrt{1 + x^2/32} + 0.1768xd/t, \\ &x = 10 \cdot d\sqrt{f}), \end{aligned} \tag{2}$$

$$\begin{aligned} &\omega \cdot m = 1.847 \frac{ft}{p} \cdot K_m, \\ &(\text{in which } K_m = 1 + \sqrt{(9 + x^2/2)} + 0.85 \cdot \frac{d}{t}, \\ &p = 78.5d^2/b^2). \end{aligned} \tag{3}$$

The sketch map of the hybrid device can be seen in Fig. 1, in which D represents the length of the back cavity, t_m is the thickness of the piezoelectric membrane, and a_m is the side length of the square membrane. Suppose that S_{cav} represents the area of the circular cross section of the cavity behind the MPP, then the impedance of the MPP Z_{MPP} will be

$$Z_{MPP} = R_{ap} + j\omega M_{ap} = \frac{Z_0 Z_r}{S_{cav}} = \frac{\rho c\,(r + j\omega m)}{S_{cav}}. \tag{4}$$

An equivalent circuit of the hybrid device is depicted in Fig. 2(a), which includes the acoustic resistance R_{ap} and equivalent acoustic mass of the air M_{ap} in the micro-perforators, acoustic capacitance of the air in back cavity C_{ac}, mechanical mass M_m, and compliance C_m of the membrane (the subscript a represents the acoustic system, and m denotes the mechanical system). The elements in the equivalent circuit can be expressed according to the MPP theory in the following equations:

$$\begin{cases} R_{ap} = \rho cr/S_{cav}, \\ M_{ap} = \rho cm/S_{cav}, \end{cases} \tag{5}$$

and

$$\begin{cases} Z_{device} = Z_{MPP} + Z_{cav}//Z_{mem}, \\ Z_{MPP} = R_{ap} + j\omega M_{ap} = \rho cr/S_{cav} + j\omega\rho cm/S_{cav}, \\ Z_{cav} = -j\dfrac{1}{\omega C_{ac}} = -j[\rho c\,\mathrm{ctg}\,(\omega D/c)]/S_{cav}, \\ Z_{mem} = j\left(\omega\dfrac{M_m}{S^2} - \dfrac{1}{\omega S^2 C_m}\right)/N. \end{cases} \tag{6}$$

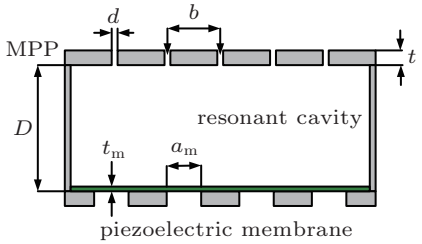


Fig. 1. Sketch map of hybrid device.

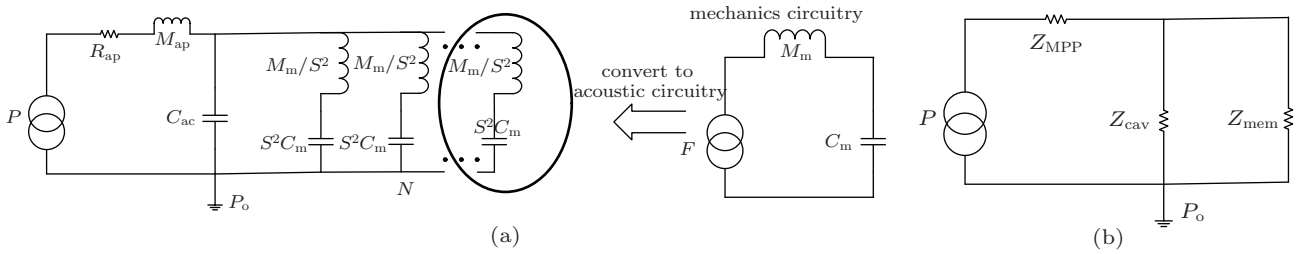


Fig. 2. (a) Equivalent circuit of the hybrid device and (b) simplified equivalent circuit.

To simplify the equivalent circuit, parameters Z_{device}, Z_{cav}, and Z_{mem} (these three parameters are acoustic impedances in different parts of the hybrid device) in Eq. (6) are assumed, so the conversion of the circuit can be shown in Fig. 2(b). Then the pressure difference exerted on the piezoelectric membrane ΔP_{mem} can be calculated, according to the principle of the circuit, from the following equation

$$\Delta P_{mem} = (P - P_0) \cdot \frac{Z_{cav} \cdot Z_{mem}}{Z_{cav} \cdot Z_{mem} + Z_{MPP} \cdot Z_{cav} + Z_{MPP} \cdot Z_{mem}}, \tag{7}$$

in which, the number of the membrane is N,

$$M_m = St_m\sigma,$$

and S is the area of the single membrane, σ is assumed to be the density of the membrane, μ is Poisson's ratio, E denotes

Young's modulus, and P is the input sound pressure. Therefore the average compliance value of a single diaphragm $C_{\rm m}$ is

$$C'_{\rm m} = \frac{\overline{\Psi}}{F} = \frac{\iint_S \Psi(x,y)\,{\rm d}x{\rm d}y}{FS} = \frac{1}{S}\iint_S C'_{\rm m}(x,y)\,{\rm d}x{\rm d}y, \quad (8)$$

where $\overline{\Psi}$ is the average displacement of the membrane and $\Psi(x,y)$ is the exact displacement. Exact compliance of a single membrane is

$$C'_{\rm m}(x,y) = \frac{49\left(1-\mu^2\right)\cdot t_{\rm m}}{192E}\left(\frac{a_{\rm m}/2}{t_{\rm m}}\right)^4 \times \left(\frac{4x^2}{a_{\rm m}^2}-1\right)^2\left(\frac{4y^2}{a_{\rm m}^2}-1\right)^2.$$

So the total compliance $C_{\rm m}$ can be expressed as

$$C_{\rm m} = \frac{N\iint_S C'_{\rm m}(x,y)\,{\rm d}x{\rm d}y}{S}. \quad (9)$$

When $P-P_0 = 1$ Pa, the pressures exerted on the membrane at different frequencies can be observed in Fig. 3. Suppose that the acoustic wave can be expressed as $p_{\rm in} = p_{\rm a}\exp({\rm j}\omega t)$, the velocity of the acoustic mass is $v = v_{\rm a}\exp({\rm j}\omega t)$ in a small tube, $Z_{\rm device} = R_{\rm device} + {\rm j}X_{\rm device}$ denotes the impedance of the MPP at the nozzle, and the area of perforators is $pS_{\rm cav}$. The velocity magnitude of the acoustic mass can be written as

$$|v_{\rm a}| = p_{\rm a} \Big/ \left(pS_{\rm cav}\sqrt{R^2_{\rm device}+X^2_{\rm device}}\right)$$

in the tube, when the resonant frequency $f = 3000$ Hz, $X_{\rm device} = {\rm j}\omega M_{\rm ap} - Z_{\rm cav}//Z_{\rm mem} = 0$. As a result, the pressure of the acoustic mass is equivalent to the pressure of the membrane and acoustic cavity, thus the pressure of MPP's reactance part is zero. At this time, $|v_{\rm a}|$ may achieve its maximum value, the resonation of the system takes place, and the absorption coefficient of the MPP equals one.

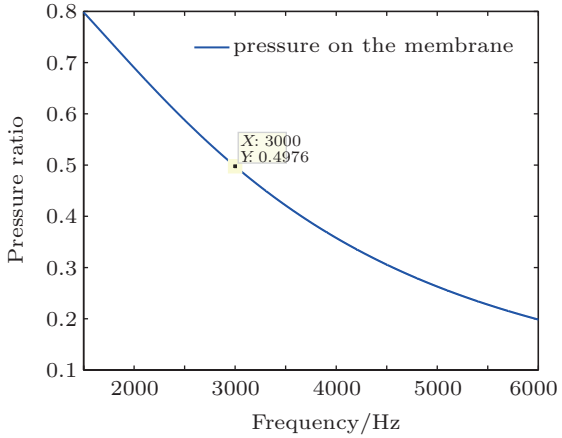


Fig. 3. (color online) Pressures exerted on the membrane at different frequencies by MATLAB simulation, with the parameters of the membrane being $a_{\rm m} = 4$ mm, and $t_{\rm m} = 1$ μm.

3. Design and fabrication

3.1. MPP element

The MPP structure is designed based on the previous theory, and the optimized parameters of the MPP can be calculated from Eqs. (1)–(3). The results are as follows: the diameter of the micro-perforator $d = 100$ μm, the distance between the perforators $b = 400$ μm, and the thickness of the panel $t = 290$ μm. Other parameters of the MPP are listed in Table 1. The dense micro-perforators can be shaped with the accurate dimension based on MEMS technology.

Table 1. Parameters of the MPP resonant structure.

Diameter	Panel thickness/μm	Perforators distance/μm	Resonant frequency/Hz	Back cavity/mm	Band width	Maximum absorption coefficient
100	290	400	3000	19.62	2.215	0.99

Firstly, an LPCVD Si_3N_4 300-nm thick is deposited on the surfaces of the wafer to serve as the protection layer, and then the wafer is immersed in the KOH solution for reducing the thickness to a desired one. Secondly, an aluminum layer with a thickness of 300 nm is evaporated onto surface to be used as the etching cover layer, the AZ1500 positive photoresist is used in the lithography process to form the micro-perforator array pattern, and then the wafer is etched in the deep reactive ion etching (DRIE) process. Finally the wafer is placed into acetone and pure H_3PO_4 solution in sequence to eliminate photoresist and residual aluminum layers respectively. The fabrication process flowchart is shown in Fig. 4(a).

3.2. Piezoelectric membranes panel element

The piezoelectric energy harvesting membrane is composed of an SiO_2 layer, an Si_3N_4 insulation layer, a bottom electrode layer, a ZnO piezoelectric layer, and an up electrode layer in accordance with the order from bottom to top. The piezoelectric membrane should be as thin as possible, which is because the pressure of the acoustic wave is so small in the audible spectrum. In order to obtain a large strain, the membrane is designed and fabricated with a dimension of 4 mm×4 mm in a square as large as possible, and the thickness is about 2 μm.

The fabrication process of the piezoelectric membrane

starts with the SiO_2 and Si_3N_4 layers grown on the surfaces of the cleaned silicon wafer in sequence. Lithography and development processes are used to produce square arrays from the backside of the wafer, so that the exposed SiO_2 and Si_3N_4 layers can be eliminated for opening the windows to form the square membrane by wet etching. Afterward there are three steps to fabricate the piezoelectric sandwich membrane structure on the other side of the wafer. A layer of platinum is sputtered to be used as the bottom electrode and pads. The ZnO layer and the up electrode platinum layer are sputtered onto the bottom electrode layer in sequence by the lift off process. The detailed fabrication schematics can be seen in Fig. 4(b).

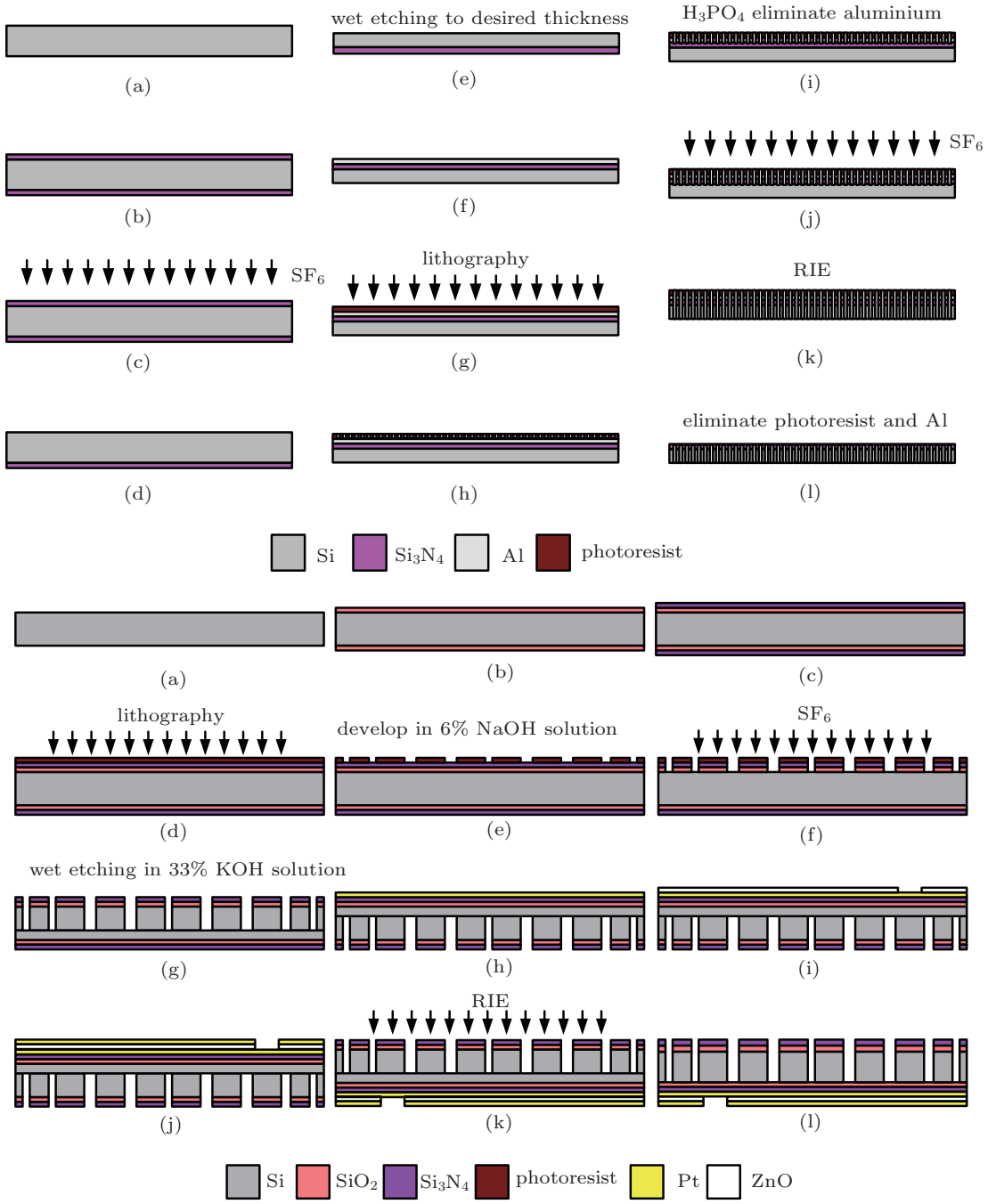


Fig. 4. (color online) Fabrication schematics of (a) the MPP panel and (b) the piezoelectric membrane panel.

The photograph of the MPP is exhibited in Fig. 5(a), in which the dense perforators on the panel can be seen clearly. Figure 5(b) displays the picture of the perforators that are observed by microscope, the margins of the micro-holes are clear, the perforators are arranged in order. Profiler is used for the precise thickness measurement in which an error of 2.5 μm can be found between the actual and the designed dimension. Figure 5(c) is the photograph of the piezoelectric membrane.

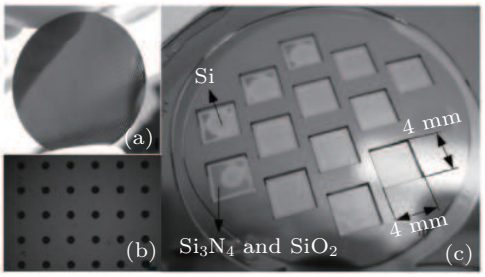


Fig. 5. Pictures of the MPP and piezoelectric membranes panel.

3.3. Hybrid device package

The MPP for noise reduction structure is composed of a panel and a cavity. A metal bracket is designed and fabricated for the hybrid device package. The MPP panel, the bracket, and the piezoelectric membrane panel are assembled to form a resonant cavity. The front and bottom side of the device are shown in Figs. 6(a) and 6(b) respectively. Figure 6(b) shows the piezoelectric membrane panel. The conductive silver paste is used to connect the up electrode layer and to adhere to the bottom panel and bracket as well. The bottom electrode layer is conducted onto the printed circuit board, two wires from the bracket and the printed circuit board can be used to extract the electricity produced by the piezoelectric layer. The resistance between the up and bottom electrode is about 8 Ω, a thicker ZnO layer or PZT layer might have a larger resistance.

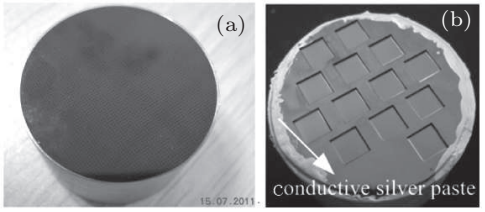


Fig. 6. (a) Top view and (b) bottom view of the hybrid device. Assembly pictures of MPP, the piezoelectric membranes panel, and the brass bracket.

4. Results and discussion

Two kinds of MPP devices are assembled for comparing their acoustic absorption properties. One is the MPP cavity with a rigid bottom. The other is the MPP cavity assembled with the piezoelectric membranes panel (defined as the hybrid device). The noise absorption coefficient experiment is carried out in the anechoic chamber. The acoustic–electric measurement system supplied by Hangzhou AiHua Instruments Company is employed to accomplish the vertical incident noise absorption coefficient measurement. The AWA6122A standing wave tube is the critical part of the system. The acoustic noise source is a AWA77 speaker, the sound power range is from 35-dB to 136-dB SPL, and the frequency range is from 1500 Hz to 6500 Hz.

Experimental results reveal that the acoustic absorption effect of the rigid bottom MPP device is pretty good. The average absorption coefficient is higher than 0.75, and it is very consistent with the prediction of the theory. This might be because the MEMS fabrication technology enhances the precision of the structure. The acoustic absorption bandwidth is expanded obviously by reducing the diameters of the microperforators, and it reaches up to 2.215. The acoustic absorption effect of the membrane bottom MPP device is tested under the same condition for comparison. The results show that the absorption coefficient of the device is a bit lower than that of the rigid bottom MPP device especially at high frequency. But the device is still a good acoustic noise absorber, whose average absorption coefficient is higher than 0.7. The results of both the rigid bottom MPP device and the membrane bottom MPP device are all exhibited in Fig. 7 for an easy comparison. The circles denote the tested results of the MPP with a rigid bottom, and the solid line represents the prediction of the theory. The star and dash line refer to the experimental results of the hybrid MPP device.

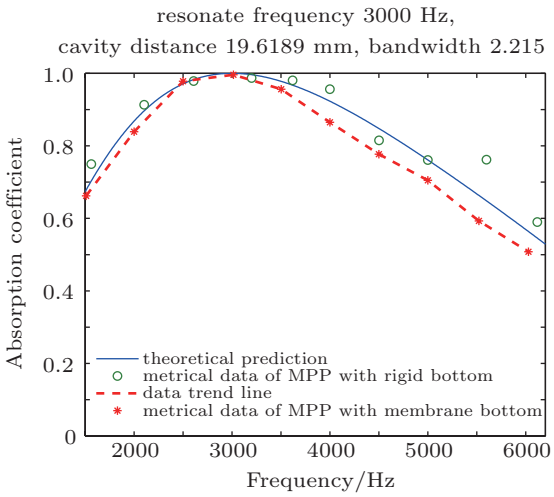


Fig. 7. (color online) Absorption coefficients of two kinds of MPP devices.

The phenomenon that the acoustic absorption coefficient of the hybrid MPP device is lower than that of the rigid bottom MPP device might be because of the membrane itself. The absorption coefficient equation of the traditional MPP is

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \mathrm{ctg}\,(\omega D/c))^2}. \tag{10}$$

The conclusion $Z_{\mathrm{cav}} \parallel Z_{\mathrm{mem}} < Z_{\mathrm{cav}}$ is able to be drawn from Fig. 2(b) ("$\parallel$" represents that two impedances are paralleled). So $\mathrm{ctg}\,(\omega D/c)$ decreases in the hybrid MPP device. As a result, the absorption coefficient of the hybrid MPP device will decline.

The energy harvesting characteristics of the hybrid MPP device are also investigated. A bridge and a capacitor are used

to establish the electric harvesting circuit as shown in Fig. 8. The function of the bridge is to transfer the alternative voltage into the direct voltage which is charged on the capacitor, and the voltage produced by the piezoelectric layer can be observed by a voltage meter. The acoustic absorption coefficients are also tested and recorded when the device is connected to the electric harvesting circuit.

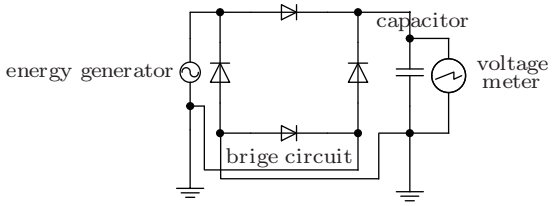


Fig. 8. Electric harvesting circuit.

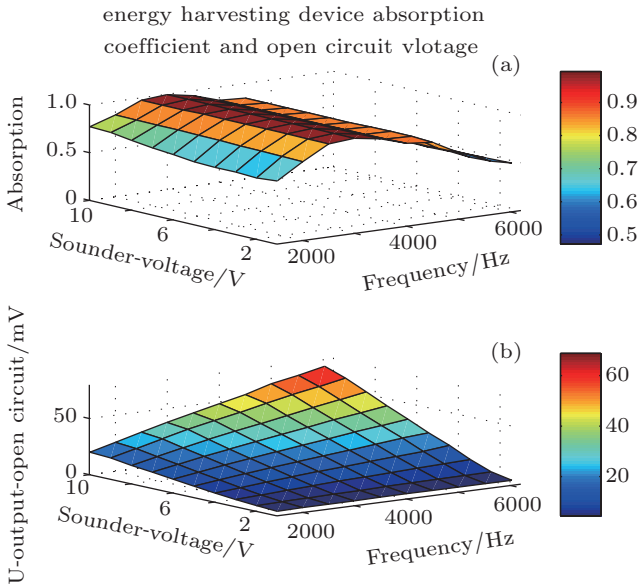


Fig. 9. (color online) Absorption coefficient (a) and open circuit voltage (b) of hybrid MPP device.

Experiments are carried out to inspect the changes of the acoustic absorption coefficient and open circuit voltage with the frequency and sounder voltage. Figure 9(a) shows the acoustic absorption coefficient, and figure 9(b) displays the open circuit voltage, indicating the maximum acoustic absorption at a resonant frequency of 3000 Hz. It indicates that the hybrid MPP device has a good capability of acoustic noise absorption. The open circuit voltage values become higher gradually with the increasing of both the frequency and the sounder voltage. The maximum voltage is 69.41 mV (in Fig. 9(a)) at the largest frequency and sounder voltage given by the experimental setup. A reasonable conclusion can be drawn that larger single strain and higher frequency can increase the output voltage. The base harmonic frequency of the vibrant membrane is much higher than 6500 Hz because of the small mass and the stress of the film, as a result the strain is tiny and it will increase with the rising of frequency in the whole spectrum that has been tested. So, higher frequency becomes a critical factor for enhancing the output voltage based on the analysis above. Load voltage and acoustic absorption coefficient data of the hybrid MPP device are illustrated in Fig. 10, and the load voltage is low compared with the open circuit voltage with a resistance of 43.246 kΩ, while their trends of variation are similar. The maximum output power of the hybrid MPP device is about 1.41×10^{-5} W/m^2.

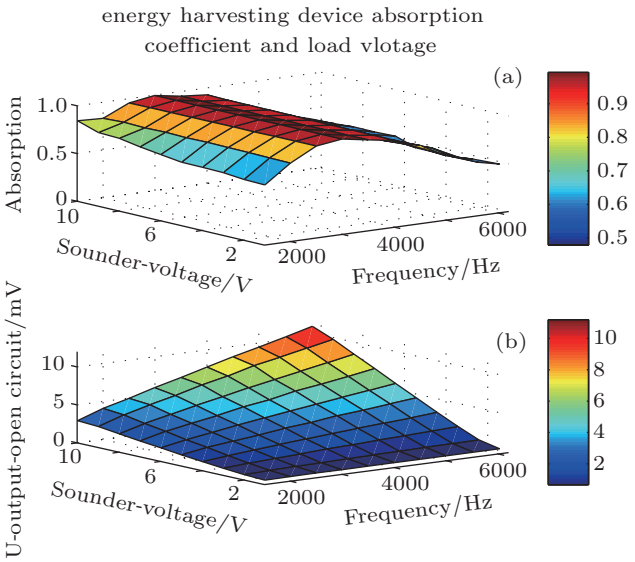


Fig. 10. (color online) Absorption coefficient (a) and load voltage (b) of hybrid MPP device.

The acoustic–electric conversion efficiency can be characterized by the sensitivity of the piezoelectric film. The sensitivity can be calculated based on the results above. Let ΔP be the acoustic pressure difference of the MPP, $p_0 = 2\times10^{-5}$ Pa the reference acoustic pressure, and S the sensitivity of the piezoelectric film, then, according to the equation of decibel and pressure $SPL = 20\lg\Delta P/p_0$, when $SPL = 136$ dB, $\Delta P = p_0\cdot10^{6.8}$, we will have $\Delta P_{\rm mem} = p_0\cdot10^{6.8}\cdot2\cdot10^{-1}$. The conclusion $S = 2.75$ mV/Pa can be obtained.

Experimental results and the piezoelectric film properties are closely related to each other. Good orientation and piezoelectric characteristic of the film can surely make the film harvest the noise vibration energy successfully. While due to the small mass and stress of the Pt/ZnO/Pt/SiO_2/Si_3N_4 film, the resonant frequency is high. Besides, PZT material is able to be employed in the device, for its piezoelectric coefficient is larger than that of ZnO material. Existing research shows that PZT materials would enhance the performance of the device.[11]

5. Conclusion

A novel hybrid device with functions of acoustic noise reduction and vibration energy harvesting based on the MPP theory is successfully developed, which is designed and fabricated based on MEMS technology. The micro-fabrication technology can precisely design the MPP structure, which would increase the absorption coefficient of acoustic noise and expand the bandwidth. In addition, the hybrid MPP device is integrated with an energy conversion element for converting the acoustic noise to electricity. The purpose of the hybrid device is realized by theory analysis, MEMS design, and fabrication.

The results show that the hybrid device has a good performance. However, the progress is still primary. In the future a thicker ZnO layer or PZT layer may be used to enhance the output power effectively.

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