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特气室温红外探测器的噪声分析

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摘要：由 MEMS 技术制备的特气室温红外探测器的噪声主要包括温度噪声、机械热噪声和背景噪声。从理论上建立了器件的基本热模型，推导得到器件的等效热熔和等效热导分别为 8.1 μJ/K 和 1.0×10^{-3} W/K，温度噪声约为 1.73×10^{-10} W/Hz$^{1/2}$；通过器件的工作机理和能量均分原理，推导得到热机械噪声的等效噪声功率约为 9.96×10^{-9} W/Hz$^{1/2}$，器件的背景噪声约为 3.22×10^{-11} W/Hz$^{1/2}$，从而得出器件的归一化探测率约为 9.03×10^{6} cm・Hz$^{1/2}$/W。实验表明，器件的噪声中热机械噪声为主要噪声源，大小主要由浓硼硅薄膜的机械性能和器件结构决定，可以通过增大薄膜厚度，减小薄膜面积，从而增加薄膜的特征频率的方法来减小器件受外界振动的影响，但以降低器件的灵敏度为代价。另外环境振动噪声也对器件的影响很大。为了减小外界气压和温度变化的影响，提出了一种新型的双腔结构来减小和平衡外界环境变化引入的噪声。

关　键　词：红外探测器；温度噪声；热机械噪声；等效噪声功率；微机电系统
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Noise analysis of special-gas IR detector

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Abstract：The noises of a special gas IR detector fabricated by MEMS mainly include the temperature-fluctuation noise，mechanical-thermal noise and the background noise. Based on thermal conduction theory，a thermal model is built up to get the effective thermal content and the effective thermal conductivity to be 1.0×10^{-3} W/K and 8.1 μJ/K，respectively ，and the temperature-fluctuation noise is nearly 1.73×10^{-10} W/Hz$^{1/2}$. According to the device operating principle and energy equipartition theory of thermodynamics，the mechanical-thermal noise is 9.96×10^{-9} W/Hz$^{1/2}$，and the background noise is nearly 3.22×10^{-11} W/Hz$^{1/2}$，so that the normalized detectivity is deduced to be 9.03×10^{6} cm・Hz$^{1/2}$/W. Experiment results show that the mechanical-thermal noise coming from the structure and the mechanical performance of a heavily doped Si membrane is the main noise of the device，which can be reduced by minishing the membrane area and extending the membrane thickness to increase the mechanical resonant frequency of the membrane，but should be at the price of reducing the sensitivity of the device. The vibration of environment also influences on the device a lot. To decrease the noise coming from the fluctuation of air pressure and the temperature fluctuation of the surrounding，a new

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double-cell counteracting structure is presented.

Key words: infrared detector; temperature-fluctuation noise; mechanical-thermal noise; Noise Equivalent Power(NEP); MEMS

1 Introduction

The detection of infrared (IR) radiation is very important for a variety of activities in both commercial and defence areas[1-2]. Generally, special-gas IR detectors inherited the strong points of thermal detectors, using special gas absorbing characters at certain wavelengths as medium and fabricating gas cells with elastic sensitive films and micro-capacitance structures by Microcelectric-maching technology (MEMS)[3-5]. Compared with normal thermal detectors, the less thermal capacity leads to faster response. The detector uses a special gas as the absorbing medium, without the heat transform process from solid to gas. The special-gas structure is much smaller than that of other detectors using optical measurements, and all the structures can be integrated. The detector array is also available.

The smallest signal that the detector can test is decided not only by its sensitivity, but also by the NEP(Noise Equivalent Power). During testing, there are several kinds of noises, such as temperature fluctuation, thermal-mechanical noise and so on. Those noises would degrade the performance of the detector and decrease the ratio of the signal to noise so that to analyze the relationship between the noise and the structure or factors is necessary and important. And some solutions should be taken to reduce the noise. In this article, the noises of the device are analyzed and the measures to reduce the noise are discussed.

2 Structure and principle of device

The structure of a special-gas IR detector is shown as Fig. 1:

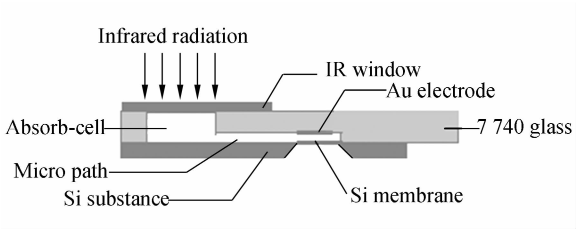

Fig. 1 Structure of micro capacity IR detector

The gas sealed in the cell absorbs the IR and expands. Through the micro path, the pressure works on the membrane, and makes the membrane deflect. The capacitance composed of the Au electrode and the movable Si membrane decreased. By measuring the change of the capacitance, we can get an infrared radiation signal.

3 Noises of device

The noises of the device mainly conclude: the temperature-fluctuate noise, mechanical-thermal noise and the background noise.

3.1 Noise of temperature fluctuation[6]

The heat exchange between the gas and the surrounding environment influences the pressure, and makes the signal fluctuate. When the detector works in steady-state, the highest temperature is at nearly the middle of the absorbed cell[7]. Thermal conductance from the gas to the IR window is given by:

$$G_{\mathrm{gas1}} = G_{\mathrm{gas}} \times \frac{A}{d} = (1.4\times10^{-4}\,\mathrm{W/(cm\cdot K)}) \times \frac{0.38\ \mathrm{cm}^2}{0.1\ \mathrm{cm}} = 5.3\times10^{-4}\,\mathrm{W/K}\ . \tag{1}$$

Where G_{gas} is the thermal conductivity of special gas, A is the area of the absorb-cell, d is the depth of the absorbing cell.

Thermal conductance between the upper IR window and the surrounding room air is given by:

$$G_{\mathrm{top\_air}}=h_q\times A=(1\times10^{-3}\,\mathrm{W/(K\cdot cm^2)})\times 0.09\ \mathrm{cm}^2=9\times10^{-5}\,\mathrm{W/K}\,. \tag{2}$$

Where h_q is the coefficient of heat convection of the air.

Thermal conductance along the micro-path to the test cell and the thermal conductance between the membrane and the surrounding is given by

$$G_{\mathrm{gas2}}=(1.4\times10^{-4}\,\mathrm{W/cm\cdot K})\times\frac{7\times10^{-4}\ \mathrm{cm}^2}{0.7\ \mathrm{cm}}=1.4\times10^{-7}\,\mathrm{W/K}\ ,$$

$$G_{\mathrm{mem}}=4\pi(G_{\mathrm{Si}})\times t=1.97\times10^{-3}\,\mathrm{W/K}\,. \tag{3}$$

Where G_{Si} is the thermal conductivity of Si, and t is the thickness of the membrane.

Because the thermal capacity of the glass is much bigger than that of the gas sealed in the cell, we assume that the heat conducted from the gas to the glass sidewall is transmitted to the room air directly, and the thermal conductance from the gas to the sidewall can be given by:

$$G_{\mathrm{glass}}=h_q\times A_s=(1\times10^{-3}\,\mathrm{W/(K\cdot cm)^2})\times\pi\times 0.3\times0.1\ \mathrm{cm}^2=9\times10^{-5}\,\mathrm{W/K}\,. \tag{4}$$

Where A_s is the area of the sidewall.

The heat capacity of the gas and the upper IR window is given by

$$C_{\mathrm{gas1}}=(2.1\times10^{-4}\,\mathrm{J/(cm^3\cdot K)})\times(3.848\times10^{-2}\,\mathrm{cm}^3)=8.1\times10^{-6}\,\mathrm{J/K}\ , \tag{5}$$

$$C_{\mathrm{top}}=k\cdot\rho\cdot V=7.6\times10^{-3}\ \mathrm{J/K}\,. \tag{6}$$

The capacity of the membrane and the gas trapped in the path and the testing cell is given by

$$C_{\mathrm{gas2}}=(2.1\times10^{-4}\,\mathrm{J/(cm^3\cdot K)})\times(1.225\times10^{-4})\mathrm{cm}^3=2.57\times10^{-8}\,\mathrm{J/K}\ , \tag{7}$$

$$C_{\mathrm{mem}}=(1.6\ \mathrm{J/(cm^3\cdot K)})\times(9\times10^{-6})=1.44\times10^{-5}\ \mathrm{J/K}\,. \tag{8}$$

These heat capacities and thermal conductance are arranged in a thermal model of the device as shown in Fig. 2. Because the thermal resistance of the micro path is much higher than that of the other paths′, it can be taken as a thermal open. Thermal flux through it can be omitted. This detector thermal model is nearly equivalent to a static heat conductance of 1.0×10^{-3} W/K, an effective heat capacity of 8.1 μJ/K, and a simple time thermal constant 52 ms, with corresponding 3 dB point at 19.7 Hz.

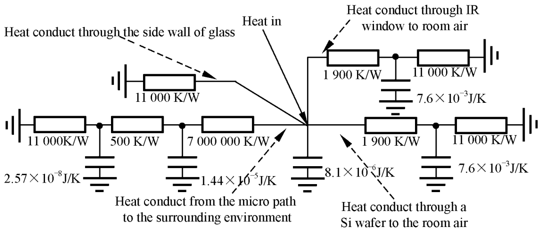

Fig. 2 Thermal model of the IR sensor. Heat is absorbed by the gas sealed in the cell, and is conducted through the gas in the cell to the upper IR window and the substance of Si wafer, and through the micro-path transverse conduct to the Si membrane made by EPW etching.

And the temperature-fluctuate noise is given by[8]:

$$\mathrm{NEP}_{\mathrm{TF}}^2=4K_{\mathrm{B}}T^2G_{\mathrm{eff}}B=1.73\times10^{-10}\,\mathrm{W/Hz^{1/2}}\ , \tag{9}$$

where, B is the testing bandwidth and we get 1 Hz as a typical value.

3.2 Mechanical-thermal noise

To the MEMS device, the small moving parts are especially susceptible to the mechanical noise resulting from molecular agitation[9]. At thermal equilibrium status, the energy of membrane oscillator is equal to the energy of single degree of freedom.

$$\frac{1}{2}k\langle x^2\rangle=\frac{1}{2}k_{\mathrm{B}}T\ , \tag{10}$$

Where $\langle x^2\rangle$ is the average of the spectral density of x^2 over all frequencies. And the fluctuation pressure on the membrane is also given by:

$$p=\sqrt{4k_{\mathrm{B}}TR_{\mathrm{acs}}}\ [\mathrm{Pa/Hz^{\frac{1}{2}}}]\ , \tag{11}$$

($R_{\mathrm{acs}}=R/S^2$, where S is the area of the membrane, R is given by $R=\dfrac{3u_aS^2}{2\pi h^3}$, u is the viscosity of the gas (1.8×10^{-5} kg/(m · s) for air at 20 ℃), h is the distance of the Au electrode and the Si substance, nearly 10 μm)

To the special-gas IR detector, the mechanical-thermal noise is related to the principle of the device.

$$\mathrm{NEP}_{\mathrm{TM}} = \sqrt{4k_{\mathrm{B}}TR_{\mathrm{acs}}}\frac{\partial T}{\partial p_{\mathrm{pressure}}}\frac{\partial p_{\mathrm{pow\_in}}}{\partial T} \ , \quad (12)$$

$$K_{p-T} = \frac{\partial p_{\mathrm{pressure}}}{\partial T} \ , \quad (13)$$

And the K_{p-T} associated with the characteristics of the membrane and according to the equation of the idea gases expand.

$$\frac{\Delta V}{V_0}(1+\frac{\Delta p}{p_0}) + \frac{\Delta p}{p_0} = \frac{\Delta T}{T_0} \ , \quad (14)$$

$$\Delta V = \iint_A w(x,y)\mathrm{d}x\mathrm{d}y = \frac{0.323\ 23}{900}\frac{\Delta p a^6}{D} \ , \quad (15)$$

$D = \frac{Et^3}{12(1-v^2)}$ (where $w(x,y)$ is the deflection of the square film, and the Δp is the pressure difference of the membrane, D is the stiffness of the film which is associated with the v (passion constant), E (the Young's modulus and t (thickness of the film)). Taken the typical value, t is 1 μm, v is 0.28, E is 180 GPa, $V_0 = 3.859 \times 10^{-8}\ \mathrm{m}^3$, we can get the $K_{T-P} = 13.95$ Pa/K. And if the radiation at 10.8 μm with the power 1 mW/cm^2, the average temperature rising is about 0.027 K[7]. So we can get:

$$\frac{\partial p_{\mathrm{pow\_in}}}{\partial T} = \frac{1}{3} \times 10^{-2}\ \mathrm{W/K} \ , \quad (16)$$

$$\mathrm{NEP}_{\mathrm{TM}} = 9.96 \times 10^{-9}\ \mathrm{W/Hz^{1/2}}. \quad (17)$$

3.3 Background photon noise

To the thermal detector, the device works at room temperature, so the background noise is given by[10]:

$$\mathrm{NEP}_{\mathrm{B}} = (16\varepsilon\sigma k_{\mathrm{B}}T_D^5 A_D \Delta f)^{1/2} \ , \quad (18)$$

T_D is 293 K, k_{B} is Bozeman constance, σ is Steve-Bozeman constance, A_D is the area of the detector. So we can get the equal power of noise of the background is

$$NEP_{\mathrm{B}} = 3.22 \times 10^{-11}\ \mathrm{W/Hz^{1/2}} \ , \quad (19)$$

The total NEP can be given by:

$$(\mathrm{NEP})^2 = \mathrm{NEP}_{\mathrm{TF}}^2 + \mathrm{NEP}_{\mathrm{TM}}^2 + \mathrm{NEP}_{\mathrm{B}}^2$$

$$\mathrm{NEP} = 9.97 \times 10^{-9}\ \mathrm{W/Hz^{1/2}} \ , \quad (20)$$

Therefore D^*, the square root of the detector area per unit noise equivalent power of the device in a 1 Hz bandwidth will be

$$D^* = \frac{\sqrt{A}}{\mathrm{NEP}} = 9.03 \times 10^6\ \mathrm{cmHz^{1/2}/W} \ . \quad (21)$$

4 Analysis and optimization

The noise caused by temperature is decided by the effective thermal conductance, influenced by the heat exchange between the gases sealed in the volume and the surrounding environment. It can be reduced by using lower conductivity materials. But in a dynamic system, response time and delay time would expend longer. The low frequency fluctuation of pressure and temperature is vital to the device. Usually, pinhole on the membrane is used to counteract low frequency fluctuation[6], but it is hard to fabricate. And the shape and the size of the pinhole are hard to design. A new structure shown in Fig. 3 using counteracting volume to balance the change of the surrounding pressure is presented.

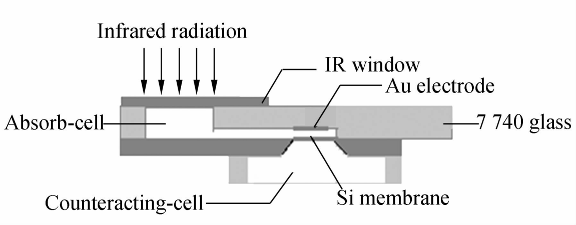

Fig. 3 Double-cell counteracting form

From (9),(17) and (19), we can see that the thermal-machine noise is the main noise of the device, and it is associated with the size of the volume, principle of the detector and the stress of the membrane. The detector is fundamentally a mechanical structure and it is sensitive to vibration. The characteristic of the membrane is mainly determined by its resonance frequencies. The resonance frequencies should be more than the testing frequencies to avoid resonance. We can get the first five vibration mode of square membrane with 1 μm thickness and 3 mm side length by using software ANSYS:

Tab. 1 The first five vibration modes of square membrane

Frequencies	Modes				
	1	2	3	4	5
f(Hz)	1 419.6	2 886.6	2 886.6	4 219.4	5 165.6

By increasing the mechanical resonant frequency of the membrane, the sensitivity to vibration can be reduced. According to its work principle of the device, the thermal-machine noise can be reduced by minishing the area and extending the distance of the two polar through viscous damping coefficient. But it is at the price of reducing the sensitivity of the device.

The photon background noise only associated with the area of the detector and the testing temperature. It is the lowest noise.

5 Conclusions

In this article, we analyze the noises of the special-gas IR detector, and the relationship between those noises and the structure of the device is discussed. A thermal model of the device is built up, and the effective thermal conductance and capacitance is deduced. The total noise equivalent power is 9.97×10^{-9} W/Hz$^{1/2}$ and the D^* is nearly 9.03×10^{6} cm · Hz$^{1/2}$/W. To decrease the noise from the fluctuations of air pressure and the temperature of the surrounding environment, a new double-cell counteracting structure is presented.

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