

Research on VO_x uncooled infrared bolometer based on porous silicon

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Abstract In this paper, vanadium oxide thin film of TCR of $-3.5\%/K$ has been deposited by pulsed DC magnetron sputtering method. The property of this VO_x has been investigated by X-ray diffractometer (XRD) and atomic force microscopy (AFM) in detail. XRD test indicates that this film is composed of V₂O₃, V₃O₅ and VO₂. VO_x microbolometer with infrared (IR) absorbing structure is fabricated based on porous silicon sacrificial layer technology. Optimized micro-bridge structure is designed and carried out to decrease thermal conductance and this structure shows good compatibility with micromachining technology. This kind of bolometer with 74% IR absorption of 8–14 μm, has maximum detectivity of $1.09 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2}/\text{W}$ at 24 Hz frequency and 9.8 μA bias current.

Keywords infrared (IR), porous silicon, microbolometer, micromachining

1 Introduction

Microbolometer is one kind of thermal infrared (IR) detector, which has a great development in recent years. It has a wide application, such as light emitting diode (LED) defect test, industrial product test and so on, due to its high performance and room temperature operation without cooling system. The incident infrared radiation is transformed into heat and temperature rise of the sensitive material causes physical property change of this material. The signal is detected by precision circuit. This is the principle of microbolometer.

Many materials can be used as sensitive materials for microbolometer, such as VO_x, which has a high negative temperature coefficient of resistance (TCR) in semicon-

ductor materials, and Ti, which has a relative high positive TCR in metal materials [1,2]. Other materials like amorphous silicon [3], silicon diode [4], etc., also have been developed in recent years.

Porous silicon technology has been used in many fields such as particle filter [5], micro-hotplates [6] and thermal sensors [7]. The purpose of utilizing porous silicon for microbolometer is to form sacrificial layer to reduce thermal conductance. Comparing with other sacrificial layers, porous silicon has these advantages: easy to be removed quickly; compatible with deposition process of thin film and compatible with the process of standard IC.

In this work, we deposit VO_x thin film of high TCR about $-3.5\%/K$. To test the property of this VO_x thin film, X-ray diffractometer (XRD) and atomic force microscopy (AFM) have been used. A research on the property of porous silicon has been investigated in detail. We integrate this film into microbolometer-based on porous silicon as sacrificial layer. The bolometer performance has been tested.

2 Vanadium oxide thin film of high TCR

As the common sensitive film, there are a lot of phases in vanadium oxide because of high TCR or transition from semiconductor to metal phase at a certain temperature. For example, vanadium oxide is mainly composed of V₂O₃, V₂O₅ and V₃O₄ [2]. In this experiment, utilizing the method of pulsed DC magnetron sputtering, vanadium oxide thin film is deposited with vanadium metal target (99.99% purity) for 15 min at argon and oxygen mixed atmosphere under optimized fabrication condition. The movement of electrons is confined near certain cathode areas by magnetic field so that probability of the gas molecules collision with electrons increases. This improves the ionization events and then the deposition efficiency. To obtain a high quality of VO_x film, the ratio of

argon gas and oxygen gas is controlled about 179 sccm:20 sccm by precise mass flow controller with 0.78 A×397 V sputtering power. During deposition process, the substrate temperature of 250°C is relatively low, which is beneficial to on-chip readout integrated circuit (ROIC) for large array microbolometer. The VO_x thin film sample for XRD test is deposited on silicon substrate with 300 nm Si₃N₄ buffer layer. Si₃N₄ film is deposited by plasma-enhanced chemical vapor deposition (PECVD) at 300°C. Semiconductor film resistance $R(T)$ and TCR can be expressed as

$$R(T) = R_0 \exp\left(\frac{\Delta E}{KT}\right), \quad (1)$$

$$\alpha = \frac{dR}{RdT} = \frac{\Delta E}{KT^2}, \quad (2)$$

where ΔE is activation energy; K is Boltzmann constant; T is temperature; R_0 is resistance constant; α is TCR. The electrical properties of VO_x film is investigated by four-probe system with precise temperature controller. This VO_x thin film shows TCR of $-3.5\%/K$ and sheet resistance at room temperature is about 128 k Ω /sq shown in Fig. 1. It appears a good linear trend from 290 to 350 K without any phase transition phenomena. The typical XRD pattern of VO_x thin film is shown in Fig. 2. The spectrum shows peaks 1 (33.0°), 2 (52.5°), 3(55.3°) that are related to the reflection from planes V₂O₃(104), V₃O₅(510), VO₂(211). No other significant peaks corresponding to other vanadium oxide are observed. The AFM photo of vanadium oxide is shown in Fig. 3. It indicates that thin film is well crystallized. The average height of crystallite is about 6 nm.

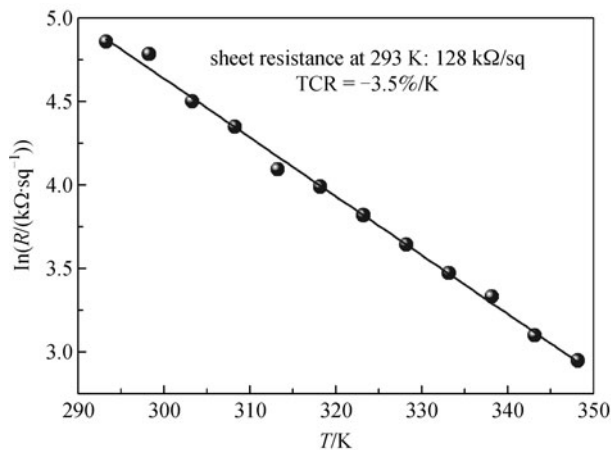


Fig. 1 $\ln(R)$ dependence on temperature for VO_x thin film

3 Preparation of porous silicon

Porous silicon is formed by the method [5–8] of anodic electrochemical etching of the silicon in the well-propor-

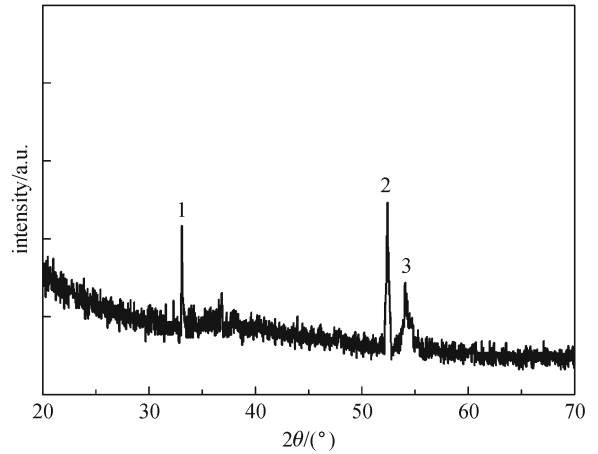


Fig. 2 XRD pattern of vanadium oxide

tioned mixture of hydrofluoric acid (HF) and hydrogen peroxide (H₂O₂) solution. The charge exchanges between dopant silicon surface and electrolytic HF and H₂O₂ forms Schottky contact results in porous silicon [9]. Photoresist is used to pattern the needed region in order to make unmasked region pore. High dopant concentration p-type (111) silicon with a low resistivity of $2 \times 10^{-2} \Omega \cdot \text{cm}$ is used to increase current flux, so that silicon can be easily porous and dissolved. Bias current is applied by Pt electrodes in double reaction tank, while the silicon is fixed in the middle of insulated baffle.

Figure 4 shows that different concentration of HF solution has influence on corrosion rate of anodic oxidation while current is stable. With the same HF solution, the corrosion rate increases as the current increases. High concentration of HF solution has a faster corrosion rate than other low concentration of HF solution. With time passing by, the depth of porous silicon becomes deeper while keeping 30% concentration of HF solution stable as shown in Fig. 5. The depth of porous silicon shows linear dependence on anodizing time in 10 min.

The two channels of porous region are removed in KOH solution as shown in Fig. 6. KOH solution dissolves two channels unmasked region. Based on this quickly dissolved sacrificial layer (only two minutes), it is suitable for micromachining of the devices. A 2.5 μm cavity length of porous silicon (9 mA/cm² bias current, 2 min) corresponds to 8–14 μm atmosphere infrared transmittance spectrum because of $\lambda/4$ resonance theory [10].

4 Process flow for microbolometer

Process flow steps are shown in Fig. 7. Firstly, the porous silicon sacrificial layer has been prepared by the method of anodic electrochemical etching as shown in Fig. 7(a). Si₃N₄/SiO₂/Si₃N₄(thickness: 200/150/200 nm) “sandwich structure” supporting layer is deposited by PECVD

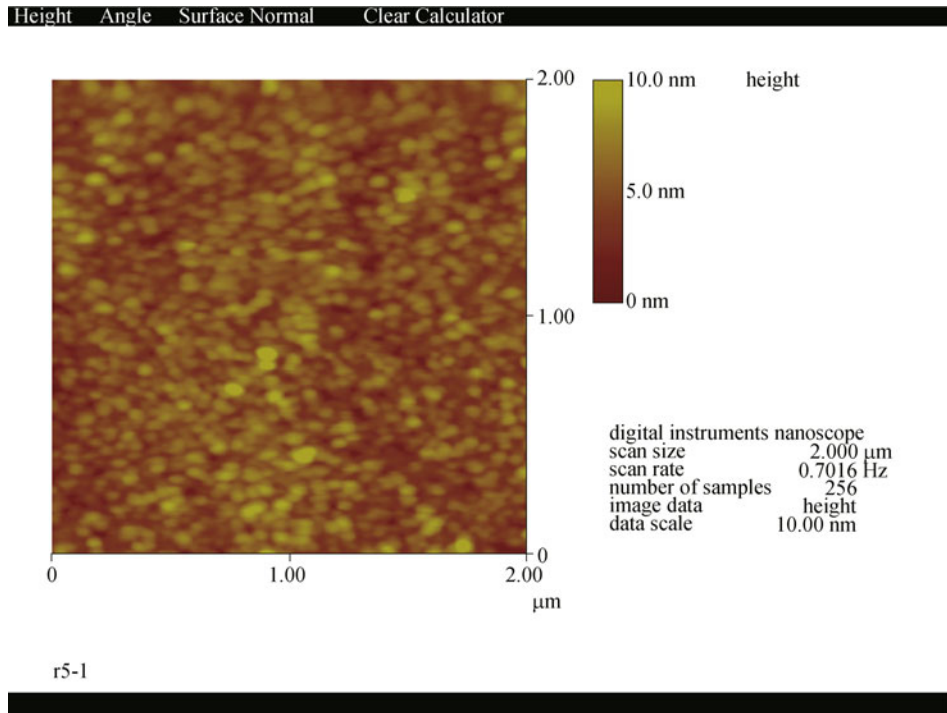


Fig. 3 AFM micrographs of vanadium oxide

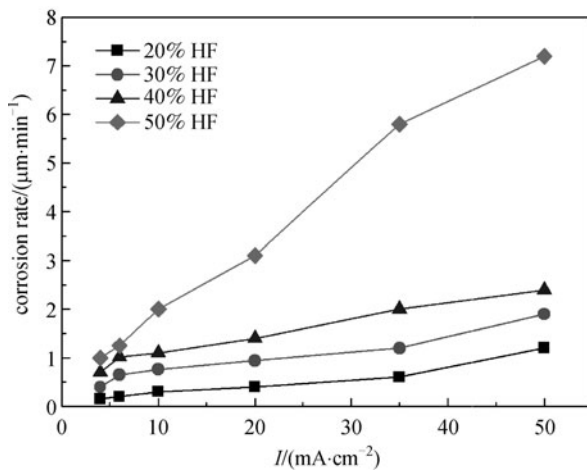


Fig. 4 Curves of corrosion rate of HF solution versus current density

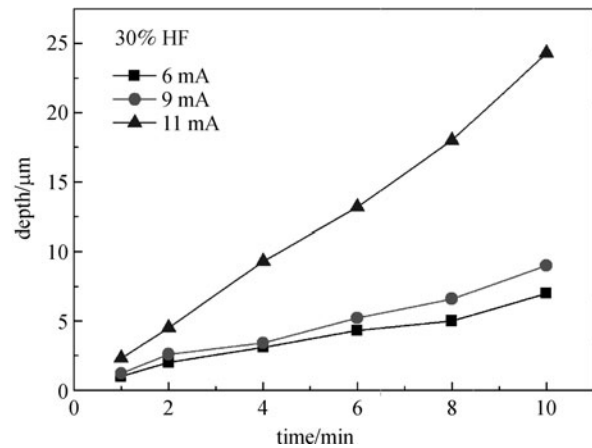


Fig. 5 Curves of depth of porous silicon versus anodizing time

(Fig. 7(b)). The sandwich structure plays roles of insulating, supporting, reducing heat-conductive and absorbing infrared. This kind of silicon dioxide/silicon nitride has advantage of well uniformity and hardness. Vanadium oxide sensitive film (150 nm) is deposited by utilizing the method of pulsed DC magnetron sputtering (Fig. 7(c)). The shape of this sensitive thin film is well patterned by wet etched method. On top of VO_x adjacent to the edge deposits a conductive layer by sputtering Cr/Au (60/100 nm). It sticks to the bottom layer well and shows a good conductivity. The conductive layer is formed by lift-off method (Fig. 7(d)). Then with the method of pulsed DC

magnetron sputtering, controlling N_2 , argon gas rates, TiN absorbing layer (300 nm) is deposited. PECVD $\text{Si}_3\text{N}_4/\text{SiO}_2$ (200/100 nm) makes further efforts to promote infrared absorption and to protect the bottom layers (Fig. 7(e)). Thus micro-bridge structure has been left to be formed. After the required shape and region have been etched to the bottom by MRIE (Fig. 7(f)), KOH solution immerses the sample only 2 min. H_2 emerges from the solution during this anisotropic wet etching process. Finally, micro-bridge structure VO_x infrared bolometer unit has been investigated by scanning electron microscopy (SEM) as shown in Fig. 8. The minimum conductive layer width of micro-

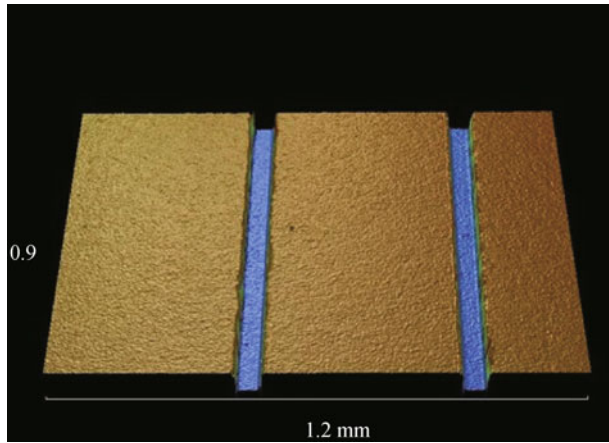


Fig. 6 Porous Si contour profile as sacrificial layer after dissolved

bridge is 5 μm . A wider metal layer (about 8 μm) connects the narrow one on one side, on the other side connects outer circuit. The VO_x sensitive region is of a circle shape whose diameter is 50 μm . All above is fully utilized for IR absorption and thermal conductance reduction.

5 Detector test

To analyze IR absorption for detector, Fourier transform infrared spectroscopy (FTIR) was used to measure the absorption. The curve is determined as the wavelength from 4–15 μm . The absorption of total films is shown in Fig. 9. The value of highest absorption at 9.87 μm reaches 98%. The average absorption of 8–14 μm is calculated to be about 74%. It means the total film system including TiN absorber is of good absorption for mid-infrared.

The vanadium oxide thin film mentioned above is compatible with CMOS technology. This thin film has been integrated into microbolometer. The bolometer sheet resistance is 128 k Ω /sq, with a TCR of $-3.5\%/K$. The bolometer is packaged in a vacuum chamber. In front of chamber is an 8–14 μm optical window, which is biased by a DC power current source. The signal is measured through a low noise pre-amplifier and a lock in amplifier. Black body source of 850°C radiates the microbolometer through a chopper frequency which ranges from 5 to 800 Hz. The chamber is pumped and kept about 10 Pa. The bolometer test system is shown in Fig. 10. The purpose of utilizing

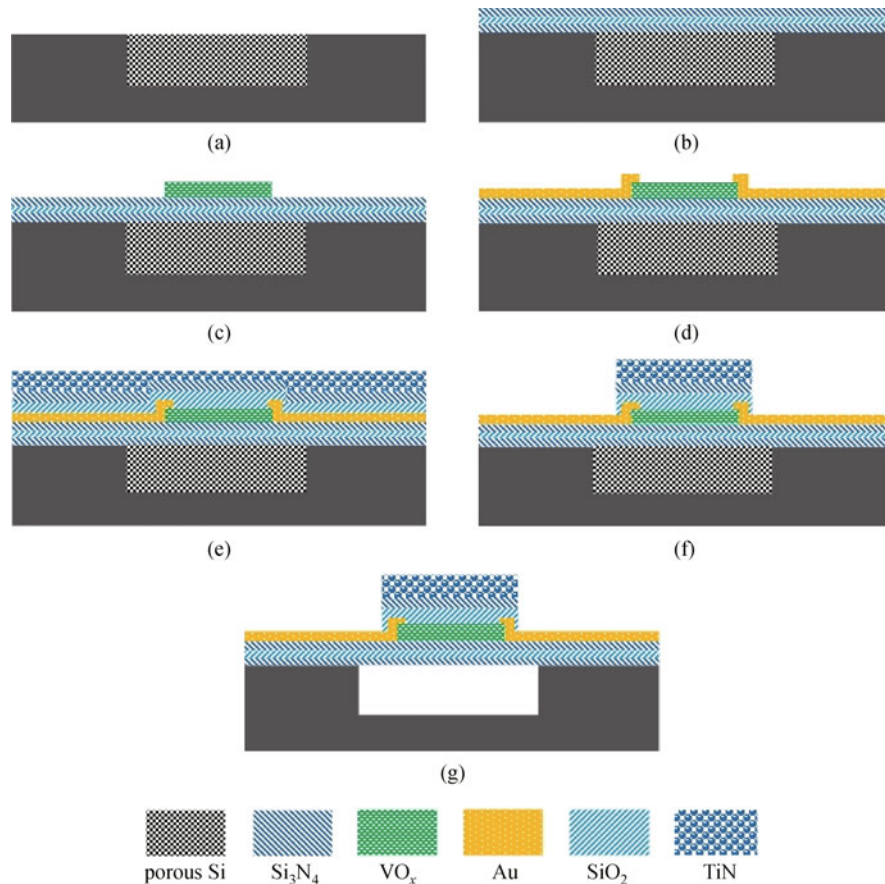


Fig. 7 Process flow of microbolometer based on porous silicon sacrificial layer. (a) Preparation of porous silicon layer; (b) deposition of supporting layer; (c) deposition and etching of VO_x; (d) deposition of conduction layer; (e) PECVD films and deposition of TiN absorbing layer; (f) etching of absorbing structure; (g) removal of porous silicon sacrificial layer

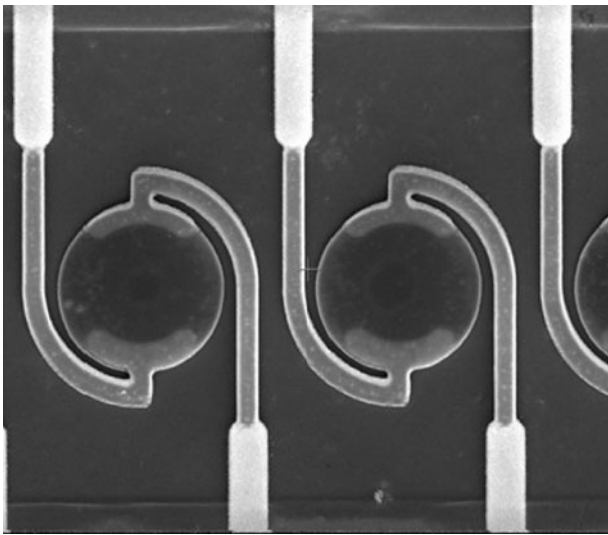


Fig. 8 Microphotography of microbolometer

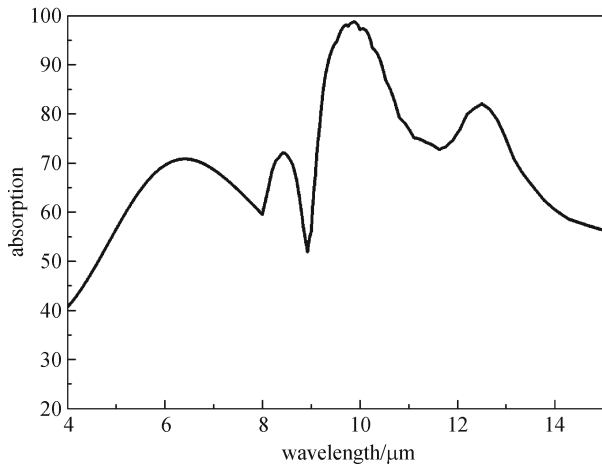


Fig. 9 Total absorption for microbolometer

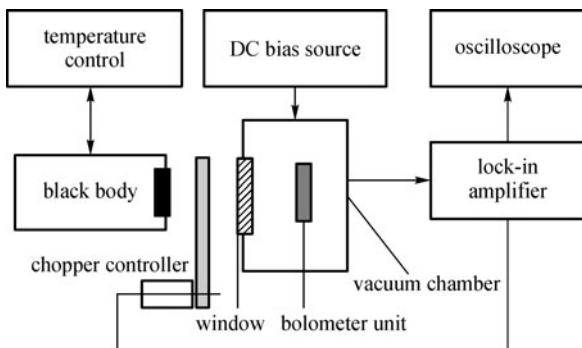


Fig. 10 Test system for VO_x bolometer

porous silicon is to form sacrificial layer to reduce thermal conductance. The total thermal conductance is composed of thermal conductance of gas atmosphere G_{gas} , supporting legs G_{leg} and material radiation G_{rad} : $G_{total} = G_{leg} + G_{gas} + G_{rad}$. Because of such a low vacuum pressure, G_{rad} and G_{gas} can be ignored. So G_{leg} is the main thermal conductance for this bolometer. The thermal time constant τ with thermal conductance G of 4.8×10^{-7} W/K was 5.4 ms, which is obtained through 3 dB frequency signal. The thermal mass C was about 2.59×10^{-9} J/K with the relation: $C = \tau \times G$. The bolometer responsivity R_v and detectivity D^* are given by

$$R_v = \frac{\alpha \eta I_b R_0}{g \sqrt{1 + \omega^2 \tau^2}}, \quad (3)$$

$$D^* = \frac{R_v \sqrt{A_d \Delta f}}{V_n}, \quad (4)$$

where α is TCR; η is infrared absorptivity; I_b is bias current applied to device; R_0 is bolometer resistance at room temperature; g is the thermal conductance; τ is thermal time constant; ω is modulation frequency. A_d is active absorptive area; V_n is noise; Δf is frequency bandwidth. The curve of responsivity R_v at 9 Hz depended on chopper frequency is shown in Fig. 11. Detector's responsivity has maximum value of 6.7×10^4 V/W and it shows decline trend especially between 30–90 Hz. Comparing with our former bolometer based on porous silicon [11], thermal conductance has been reduced from the level of 10^{-5} to 10^{-7} W/K. Due to the higher TCR of VO_x, the higher absorption and the less thermal conductance and less thermal mass, the responsivity has reached as 10 times as the former 5000 V/W. To reach the same responsivity, power consumption has only 1/10 than the former one because of the optimization of the structure, which means

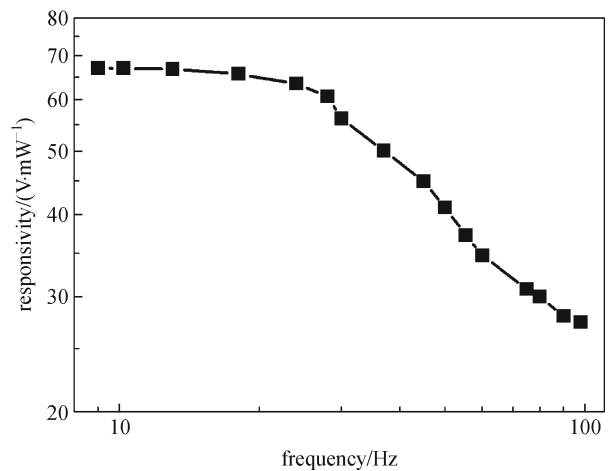


Fig. 11 Curve of responsivity (R_v) depended on frequency

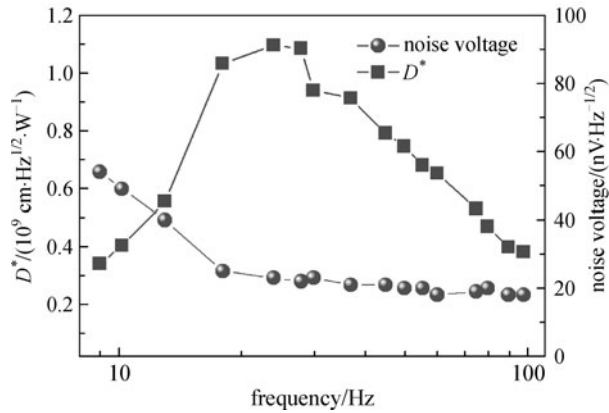


Fig. 12 Curves of detectivity (D^*) and noise voltage versus frequency

that the power consumption has been minimized greatly. The noise voltage remains a relative low level. Bolometer detectivity at 24 Hz with 9.8 μA bias current has maximum value of $1.09 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ shown in Fig. 12.

6 Conclusions

Vanadium oxide thin film is deposited and VO_x film of TCR of $-3.5\%/K$ is obtained. Based on porous silicon as sacrificial layer, microbolometer of 74% IR absorptivity is fabricated to test the performance of VO_x thin film. The results indicate that this kind of bolometer integrated into this VO_x thin film, has maximum detectivity of $1.09 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at 24 Hz frequency and 9.8 μA bias current.

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