Nb_5N_6 microbolometer arrays for terahertz detection*

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A novel room-temperature microbolometer array chip consisting of an Nb_5N_6 thin film microbridge and a dipole planar antenna, which is used as a terahertz (THz) detector, is described in this paper. Due to the high-temperature coefficient of the resistance of the Nb_5N_6 thin film, which is as high as –0.7% K^{-1}, such an antenna-coupled microbolometer is ideal for detecting signals in a frequency range from 0.22 THz to 0.33 THz. The dc responsivity, calculated from the measured *I–V* curve of the Nb_5N_6 microbolometer, is about –760 V/W at a bias current of 0.19 mA. A typical noise voltage as low as 10 nV/$Hz^{1/2}$ yields a low noise equivalent power (NEP) of 1.3×10^{-11} W/$Hz^{1/2}$ at a modulation frequency above 4 kHz, and the best RF responsivity, characterized using an infrared device measuring method, is about 580 V/W, with the corresponding NEP being 1.7×10^{-11} W/$Hz^{1/2}$. In order to further test the performance of the Nb_5N_6 microbolometer, we construct a quasi-optical type receiver by attaching it to a hyperhemispherical silicon lens, and the result is that the best responsivity of the receiver is up to 320 V/W. This work could offer another way to develop a large scale focal-plane array in silicon using simple techniques and at low cost.

Keywords: Nb_5N_6, microbolometer, responsivity, noise equivalent power

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1. Introduction

Terahertz (0.1 THz ∼ 10 THz) detectors are important components in terahertz technology.[1] Various kinds of detectors have been developed for different applications,[2] such as in spectroscopy, medicine, security, etc. However, some of them do provide high yield but need to work at liquid helium temperature, while others are not sensitive enough for many purposes, although the low-temperature requirement is optional. A compromising detector should be capable of operating at room temperature while still retaining relatively good sensitivity. One type of detector meeting these requirements is the microbolometer.[3] For room-temperature microbolometers, Bi,[4] Nb,[5] poly-Si,[6] and vanadium oxide[7] are often the candidate materials. However, the temperature coefficient of resistance (TCR) values of Bi (0.3% K^{-1}) and Nb (0.1% K^{-1}) are relatively low, which leads to low dc voltage responsivity; the typical values are approximately 99 V/W for Bi[4] and 85 V/W for Nb.[5] The detectors made of poly-Si or vanadium oxide materials have relatively high TCR values, but their excellent performance is confined in the infrared band.[6,7] Therefore, these microbolometers are rarely used in actual THz systems for reasons of typically low responsivity or excessive noise. Furthermore, MOSFET detectors[8] based on complementary metal–oxide semiconductor (CMOS) process technology have aroused great interest for their high voltage responsivity and compatibility with standard silicon microelectronic processes. Recently, we have found that Nb_5N_6 thin films grown on SiO_2/Si (100) substrates are suitable for THz detection at room temperature.[9] Such an Nb_5N_6 thin film possesses a rather large TCR, typically –0.7% K^{-1}. In this paper we present Nb_5N_6 microbolometers integrated with dipole antennas on a chip that can reach a dc responsivity of –760 V/W and a noise equivalent power (NEP) of 1.3×10^{-11} W/$Hz^{1/2}$ at a modulation frequency above 4 kHz. This work could offer another way to develop a large scale focal-plane array in silicon using a simple technique and at low cost. In this paper we discuss the design, fabrication, and performance of the Nb_5N_6 microbolometer arrays.

2. Device design and fabrication

The microbolometer consists of a gold dipole planar antenna and a microbridge, which is the core element and is made of properly patterned Nb_5N_6 thin film. To effectively couple the applied high frequency power to the Nb_5N_6 microbridge, a resonant dipole antenna[10] is used. The dipole antenna is inserted into a 120 μm × 210 μm stub, which is also used to connect to the bias circuit. HFSS software is used to carry out numerical simulations for this antenna structure. The optimal sizes are shown in Fig. 1(c). The radio frequency (RF) current distribution (Fig. 1(c)) shows conspicuous resonation on the antenna.

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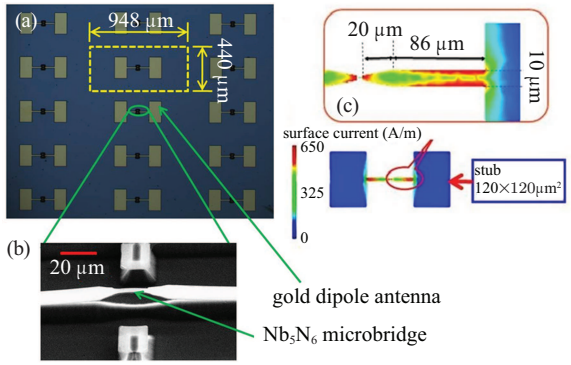


Fig. 1. (color online) (a) Image of the fabricated antenna-coupled Nb_5N_6 microbolometer array. The size of a single unit is 440 μm × 948 μm. (b) SEM micrograph of an Nb_5N_6 microbridge integrated with the antenna on an air-bridge. The micrograph is acquired by tilting the sample at an angle with respect to the horizontal plane. (c) The simulated current distribution on the antenna.

In the fabrication process of Nb_5N_6 microbolometer chips, an SiO_2/Si (100) combination substrate, i.e. a 100-nm thick SiO_2 deposited on high resistivity ($\rho > 1000$ Ω·cm) Si by thermal oxidation, is used. Such a combination is chosen because of its low loss at millimeter wave frequency and easy-fabricating air-bridges, which reduces the effective thermal conductance of the substrate to further enhance the responsivity of the microbolometers. First, we use radio frequency (RF) magnetron sputtering to deposit an Nb_5N_6 film (120-nm thick) on the substrate. The square resistance of the Nb_5N_6 thin film is about 0.9 kΩ with a TCR up to –0.7% K^{-1} at 300 K. Then, the Nb_5N_6 thin film is patterned into microbridges using photolithography and reactive ion etching (RIE). The dipole antenna is integrated with the Nb_5N_6 thin film microbridge by depositing a 5-nm thick aluminum film first, then 220-nm thick gold, and finally by using lift-off technology. Two areas near the Nb_5N_6 microbridge are first defined by patterning the substrate with photoresist and etching the surficial SiO_2 in a buffered-HF solution. The formed opening silicons are then etched by RIE to create air cavities. The RIE is carried out in SF_6 gas under a pressure of 8 Pa and a radio frequency power of 70 W. The air-bridge (Fig. 1(b)) under the Nb_5N_6 microbridge is formed by anisotropic etching 1 μm of the Si part of the substrate. The fabricated Nb_5N_6 microbolometer array chip is shown in Fig. 1(a). The resistance of the Nb_5N_6 microbridge depends on the dimension of the Nb_5N_6 film. We make three different Nb_5N_6 microbolometer array chips, whose microbridge sizes are 3 μm × 3 μm, 3 μm × 6 μm, and 3 μm × 12 μm, and their corresponding resistances are 0.9 kΩ, 1.6 kΩ, and 3.4 kΩ, respectively.

3. DC responsivity

DC responsivity is a widely used parameter to characterize microbolometers,[11] by which we can determine the maximum RF responsivity and optimal operating point of the device. The current–voltage (I–V) curve of the fabricated Nb_5N_6 microbolometer is measured at room temperature, without terahertz frequency power applied. The DC responsivity κ_E at each point on the I–V curve can be calculated using Jones' expression,[11]

$$\kappa_E = \frac{Z-R}{2I_bR}, \tag{1}$$

where $Z = dV/dI_b$ and $R = V/I_b$ are the dynamic resistance and resistance, respectively. Figure 2 shows the measured I–V curve and calculated DC responsivity κ_E of an Nb_5N_6 microbolometer with a resistance of 3.4 kΩ. It is easy to find out that the maximum responsivity is $\kappa_E = -760$ V/W at a bias current of 0.19 mA. Similarly, we obtain a maximum responsivity of –560 V/W at 0.23 mA for the microbolometer with a resistance of 1.6 kΩ, and a maximum responsivity of –366 V/W at 0.38 mA for the microbolometer with a resistance of 0.9 kΩ.

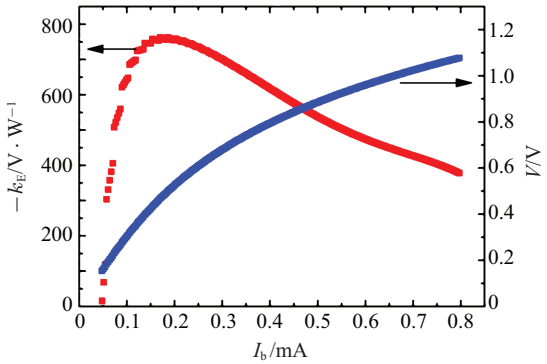


Fig. 2. (color online) The I_b–V and κ_E–I_b curves of the Nb_5N_6 microbolometer with a resistance of 3.4 kΩ. The best DC responsivity is –760 V/W at $I_b = 0.19$ mA.

4. RF responsivity

Alternatively, when a bolometer absorbs a radiant input power $P_0 + P_1 e^{j\omega_s t}$ with a steady part P_0 and a time-varying part of amplitude P_1 and modulation frequency ω_s, we can define the RF voltage responsivity κ_A as the change in voltage drop per watt of absorbed terahertz frequency power. It can be written as[11]

$$\kappa_A = \frac{\alpha I_b R}{G(1+j\omega_S\tau)}, \tag{2}$$

where α is the TCR of the bolometer, and $\tau = C/G$ is the thermal response time, with C being the heat capacity, and G the effective thermal conductance of the bolometer. Setting ω_s to zero in Eq. (2), κ_A given by Eq. (2) will be the same as κ_E given by Eq. (1). Substituting $\kappa_E = -760$ V/W found from Eq. (1) for κ_A in Eq. (2), with $I_b = 0.19$ mA, $\alpha = -0.7\%$ K^{-1}, and $R = 2.6$ kΩ, we find $G \approx 4.6 \times 10^{-6}$ W/K.

In order to test the RF responsivity of the Nb_5N_6 microbolometer, we construct a quasi-optical test system using two off-axis parabolic mirrors. The output from a signal source, whose frequency can be tuned from 0.22 THz to

0.33 THz, is focused by two off-axis parabolic mirrors. The input power at the focal spot is measured by a thermal power sensor (OPHIR, 3A-P-THz). In order to define the RF responsivity of the Nb_5N_6 microbolometer accurately, a similar infrared device characterization method is used. The energy distribution of the incident signal at the focus is scanned using our Nb_5N_6 microbolometer, with the scanning steps in the x and y axes both being 100 μm. The scan image of the incident signal at the focus is shown in the inset of Fig. 3. The responsivity $\Re$ of the Nb_5N_6 microbolometer can be described by[8]

$$\Re = \frac{\iint_{\text{focal spot}} \Delta U \, \mathrm{d}x\mathrm{d}y}{\iint_{\text{microbolometer}} \Delta U \, \mathrm{d}x\mathrm{d}y} \times \frac{\Delta U(0,0)}{P_{\text{inc}}}, \tag{3}$$

where $\iint_{\text{focal spot}} \Delta U \, \mathrm{d}x\mathrm{d}y$ and $\iint_{\text{microbolometer}} \Delta U \, \mathrm{d}x\mathrm{d}y$ correspond to the total power of the focal spot and the absorbed power by the Nb_5N_6 microbolometer, respectively, $\Delta U(0,0)$ is the output voltage of the Nb_5N_6 microbolometer, and P_{inc} is the total incident power, which is also the value obtained from the thermal power sensor. According to the DC responsivity as mentioned above, the Nb_5N_6 microbolometer is biased at 0.19 mA to obtain maximum RF responsivity. The modulation frequency is set to be 4 kHz in the experiment, and a phase-locking amplifier is used to read out the voltage response.

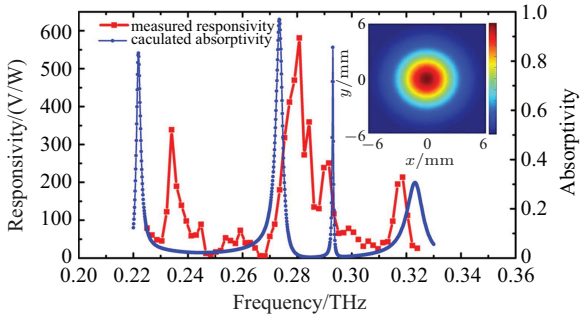


Fig. 3. (color online) The responsivity of an Nb_5N_6 microbolometer with an FP cavity, and the calculated absorptivity of the device versus frequency. The inset shows the scan image of the incident signal at the focus using the Nb_5N_6 microbolometer.

To maximize the absorption, a metallic slab is placed in the back of the Nb_5N_6 microbolometer chip. As a result, a 0.64 mm-thick Si substrate and this metallic slab constitute a metallic Fabry–Perot (FP) cavity in the direction of the incident wave. Figure 3 shows the curves of RF responsivity versus the frequency of the Nb_5N_6 microbolometer. Here, we can see four distinct responsivity peaks: the best RF responsivity is about 580 V/W at 0.280 THz, and then is followed by 330 V/W at 0.235 THz, 250 V/W at 0.290 THz, and 220 V/W at 0.318 THz, sequentially. For such a microbolometer structure with an FP cavity, the absorptivity (A) can be obtained by $A = 1 - |S_{11}|^2$. We calculate the reflection parameters S_{11} using CST MicrowaveStudio$^{\text{TM}}$ 2010. The calculated absorptivity is shown in Fig. 3. The measured responsivity and the calculated absorptivity are in substantial agreement. There is a small frequency shift at the resonance frequencies. Maybe this deviation stems from the approximate simulation model, in which we considered neither the effect of the air-bridge nor the size deviation in the fabrication process. In addition, due to the FP cavity effect, the thickness of the substrate of the microbolometer chip has a large influence on resonance frequency.

In order to further test the performance of the Nb_5N_6 microbolometer, we mount the Nb_5N_6 microbolometer chip on a hyperhemispherical silicon lens of 12 mm in diameter to construct a quasi-optical receiver. In the submillimeter wave band, an antenna-coupled bolometer is often mounted on a substrate lens to eliminate the losses caused by the substrate modes.[12] The RF responsivity of the Nb_5N_6 microbolometer receiver is measured using the quasi-optical test system mentioned above, in which the RF responsivity is calculated from the ratio of the microbolometer output voltage to the signal power, which is measured by the thermal power sensor with the incident signal irradiating on the hyperhemispherical silicon lens rather than on the microbolometer. The measured RF responsivity versus frequency of a Nb_5N_6 microbolometer receiver biased at 0.19 mA is shown in Fig. 4, from which we can see that the receiver response is good, in a range from 0.22 THz to 0.33 THz with the maximum RF responsivity being 320 V/W at 0.24 THz at a modulation frequency of 4 kHz.

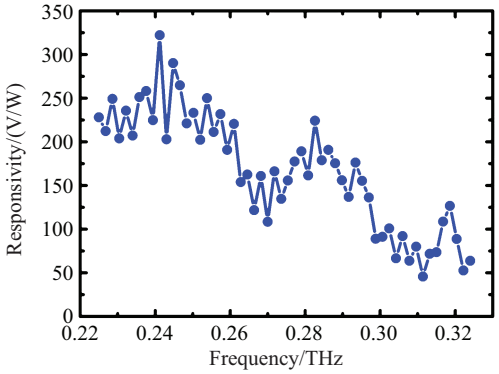


Fig. 4. (color online) The response of the Nb_5N_6 microbolometer receiver.

5. Noise equivalent power

A widely used figure of merit for a microbolometer is its noise equivalent power (NEP), which can be expressed as

$$\text{NEP} = V_{\text{n}}/R, \tag{4}$$

where V_{n} is the voltage noise spectral density (V/Hz$^{1/2}$) of the microbolometer and R is the responsivity. We use a spectrum analyzer and a low-noise amplifier (LNA, SR560) with a voltage gain of 40 dB to perform the noise spectrum measurements of the microbolometer in a shielded room. In these

experiments, what we measured is $V'_{\rm n}$, the voltage noise spectral density of the microbolometer in cascade with a low noise amplifier. Thus, the voltage noise spectral density of the microbolometer itself is

$$V_{\rm n} = \sqrt{V'^2_{\rm n} - V^2_{\rm LNA}}, \tag{5}$$

where $V_{\rm LNA}$ is the voltage noise spectral density of the amplifier.

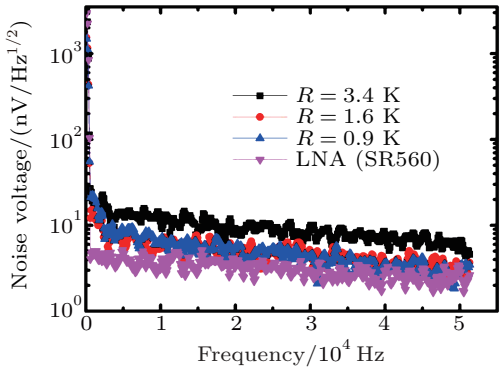


Fig. 5. (color online) Measured noise of three different sizes of Nb_5N_6 microbolometers, and the low-noise amplifier (LNA, SR560).

Figure 5 shows the measured voltage noise spectra of the three Nb_5N_6 microbolometers with resistance values of 0.9 kΩ, 1.6 kΩ, and 3.4 kΩ, respectively, and the low-noise amplifier (LNA, SR560). These microbolometers are all biased at the current where the maximum DC responsivity can be reached, as mentioned above. For all Nb_5N_6 microbolometers, we notice that the $1/f$ crossover is approximately 4 kHz, below which the device is limited by $1/f$ noise, and above which it is limited by thermal noise. When the modulation frequency is greater than 4 kHz, the noise spectrum tends to be a constant. This should be contributed only by the thermal noise itself ($\sqrt{4kTR}$). At 4 kHz, after deducting the amplifier's noise, the noise voltages of the three Nb_5N_6 microbolometers are 6.5 nV/Hz$^{1/2}$ for 0.9 kΩ, 7.8 nV/Hz$^{1/2}$ for 1.6 kΩ, and 10 nV/Hz$^{1/2}$ for 3.4 kΩ, respectively. Correspondingly, the NEPs are 1.8×10^{-11} W/Hz$^{1/2}$, 1.4×10^{-11} W/Hz$^{1/2}$, 1.3×10^{-11} W/Hz$^{1/2}$, respectively. Meanwhile, for the Nb_5N_6 microbolometer chip with a resistance of 3.4 kΩ, the best RF responsivity of 580 V/W, and the NEP of 1.7×10^{-11} W/Hz$^{1/2}$ at 0.28 THz can be reached when the modulation is 4 kHz.

6. Conclusions

In this paper, we demonstrate the design, fabrication, and characterization of an uncooled antenna-coupled microbolometer array with Nb_5N_6 thin film as its core element. It performs well as a terahertz detector for detecting signals in a frequency range from 0.22 THz to 0.33 THz, and its practical NEP is shown experimentally to be 1.7×10^{-11} W/Hz$^{1/2}$. The spectral response of the Nb_5N_6 microbolometer is limited by the structure of the antenna. Using appropriate broadband antennas[13] or metamaterial THz antennas,[14] and taking into account the impedance match between the antenna and the Nb_5N_6 microbridge, we can apply Nb_5N_6 microbolometers to much higher frequency detection. The corresponding research is now under way. Attractively, if the antenna-coupled Nb_5N_6 microbolometer array could combine a proper readout integrated circuit (ROIC), it should be a very good way to develop sensitive low-cost focal-plane arrays for THz imaging applications.

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