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Vanadium oxide linear array infrared microbolometer with a novel infrared absorption structure

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A novel long-wave infrared absorption structure containing conducting thin film of TiN_x and gold is proposed and simulated with FDTD method. This new structure has shown peak absorbance over 93% and more than 80% average absorbance at 8～12 μm theoretically. Nano-grain vanadium oxide (VO_x) uncooled 2×64 linear infrared microbolometers with this new infrared absorption structure have been successfully fabricated. The normalized detectivity of the sensing element at peak wavelength is measured to be about 6×10^8 cmHz$^{1/2}$ W^{-1}, which is feasible to practical imaging application.

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The principle advantage associated with a microbolometer technology is the ability to operate at room temperature, large temperature coefficient of resistance (TCR) and wide responsive waveband from infrared to mm wavelength [1]. However, compared to most cooled IR detectors have normalized detectivity (D^*) from 10^9 to 10^{11} cm Hz$^{1/2}$W^{-1}, bolometer-type IR detectors have some drawbacks such as low detectivity (D^*～10^8 cm Hz$^{1/2}$W^{-1}) due to self-heating under constant bias, thermal noise and process variations of thermal sensitive materials (for example VO_x) [2]. One issue to enhance detectivity of microbolometer is to increase TCR of the sensitive thin film with low noise. Conventional VO_x thin film with 1～2 microns grain size has typical TCR of -2%/K. Recently, higher TCR values have been reported in the literature. Amorphous V–W–O with TCR of -4.0%/K was developed as an infrared active material for an uncooled microbolometer, which has a detectivity over 1.03×10^9 cmHz$^{1/2}$/W at a bias current of 7.5 μA and a chopper frequency of 10–20Hz [3]. Another study found nano-grain sized VO_x have shown TCR as large as -7%/K [4]. This makes it very attractive for high sensitive detector application. Another issue in developing microbolometer array is to pursue the high infrared absorption of the detector membrane at a wide spectral band and wide angular response. Since VO_x has not sufficient infrared absorption, other infrared absorption materials are added to the detector, such as thin metal film and optical dense porous metal black [5]. Meanwhile, a resonant vacuum cavity consisting of the detector membrane and a metal reflective film is commonly used to achieve more absorption around the resonant wavelength [6]. However, the resonant infrared absorption mechanism usually have narrow spectral and angular response; moreover complex fabrication processing is needed, which may increase the cost and non expected spectral absorption due to the resonant cavity imperfections resulting from the complex fabrication process [2].

In this letter, we present a novel infrared absorption multilayer structure in aim to omit the resonant cavity and extra metal black absorption layer used in conventional bolometer detector. This simplifies the process of fabrication and immunity to the precise control for cavity thickness and its uniformity. The proposed infrared sensitive layer is basically a MDM-like multilayer structure based on TiN_x type conducting materials where M represents metal or metal–like conducting materials and D represents dielectric. Instead of used metal, MDM structure based on non-metal conducting materials can achieve wider absorption spectrum.

Metal based MDM structure is known for omnidirectional resonance at certain wavelength when the reflective phase shift cancel the propagation phase shift [7]. Unlike conventional metal MDM omnidirectional resonance structure, the infrared MDM-like multilayer adopted two different conduction materials, thin TiN_x conducting film as a partly transmission surface layer and gold as a bottom reflective layer, which is shown as a amplified part in Fig. 1. The MDM-like absorption multilayer is a suspended part of the VO_x detector element and supported by two arms over an empty cavity so that thermal isolation of this structure can be functioned. In the MDM-like multilayer, the middle dielectric layer is a combined layer containing infrared sensitive film VO_x sandwiched by other two insulator films, here Germanium (Ge) and Si_3N_4, respectively. High refractive index material Ge is chosen so that the total thickness of the absorption structure for long-wave infrared can be controlled within 1 μm. This control is necessary for VO_x

infrared detector when fast response and simple fabrication have to be considered.

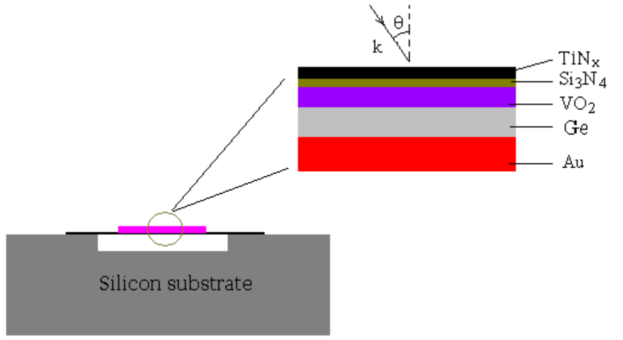

Fig. 1. Schematic diagram of a VO_x detector element with a visually amplified MDM absorption structure.

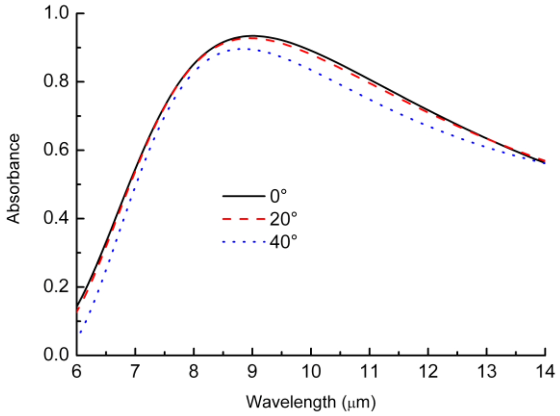

Fig. 2. Simulated absorbance spectrum with various incident angles.

To analyze the optical properties of MDM-like absorption multilayer, we employ finite-difference time-domain (FDTD) method to simulate its absorption spectrum and field distribution under plane wave illumination with various incident angles. The absorbance spectrums are deduced from the relation $A_{\lambda,\theta} = 1 - R_{\lambda,\theta}$, since no transmittance is considered due to optical thick of the bottom metallic layer. The thickness of every layer is chosen as TiN_x(70 nm)/Si_3N_4(50 nm)/VO_x(100 nm)/Ge(450 nm)/Au(100 nm). In the simulations, the optical constants of fabricated TiN_x thin film with a resistivity of 0.5 mΩ·cm are obtained from Drude model with parameters fitted from experimental measured reflection spectrum by means of Levenberg-Marquardt gradient method [8]. A freshly evaporated aluminum film was used as a reference. Optical constants of other materials are obtained from Handbook [9].

It can be seen from Fig. 2 that more than 80% absorbance can be obtained in the long-wave infrared window 8-12 μm, with peak absorbance reaching 93% at 9 μm for normal light illumination. Omnidirectional absorbance is clearly seen in this figure and only slight decrease is happened when the incident angle reaches 40°. Simulations with larger angles 60 to 80° have been tried and still show peak absorbance higher than 70% for this kind of absorption structure, though the peak wavelength is slightly shift to shorter wavelength. It is noted that, compared to the relatively poor conductivity film TiN_x, metals like Au or Ag have good conductivity and show narrower and stronger resonance properties, therefore showing narrower and stronger absorbance band. But for wide band imaging application, conducting films with less conductivity like TiN_x can receive more infrared radiation energy and then achieve higher response.

To fabricate the VO_x linear detector array containing MDM-like absorption layer, porous silicon sacrifice layer process was employed to the thermal isolation empty cavity. The formation process of PS has been well established for many years, its preparation and etching are simple and inexpensive, and is very suitable to fabricate linear array devices [10]. The fabrication starts with a P-type silicon (111) with a resistivity of $2\times10^{-2}\Omega\cdot cm$. The PS fabrication as the first step is to pattern and expose the predefined open windows of the silicon surface in an HF48%: Ethanol solution with concentration ratio 1:1 and then form PS in the window by electrochemical etching. The etching depth is usually 1 to 2 microns and no precise depth control is desirable for this kind of devices. It is worth noting that the MDM-like absorption multilayer films were fabricated by sputtering method. Ge film was deposited by Ar ion beam sputtering from a 3 inch Ge target with purity of 99.99% in Ar gas; VO_x was also deposited by reactive ion beam sputtering from a 3 inch V target with purity of 99.99% in a Ar-O_2 gas mixture; Silicon nitride insulator was deposited by radio frequency sputtering from a silicon target in a Ar-N2 gas mixture at the total pressure of 0.8 Pa with 10% N_2 concentration; TiN_x film was deposited by RF sputtering the Ti target with purity of 99.99% in a Ar-N_2 gas mixture at the total pressure of 1.0 Pa , thus forming TiN_x film on the substrate with x values varying from 0.86 to 1.13 when the N_2 partial pressure changed from 1% to 25%. The preparation process of VO_x film is the same as that previously reported and how nano-scale grain and high TCR of -7%/K [4] .

Infrared absorption properties of fabricated MDM-like multilayer structure on a double-polished silicon substrate is first examined as shown in Fig. 3. It was obtained through reflective spectrum measured by FTIR microspectrometry (Vertex 70, Bruker) with a microscopy object lens having a field of view of 10 degrees. The multilayer film parameters are chosen according to the designed data mentioned above. It can be seen that the infrared absorption of MDM-like structure is close to the designed curve at the designed wavelength, which demonstrates the MDM-like absorption structure is appropriate to detector application.

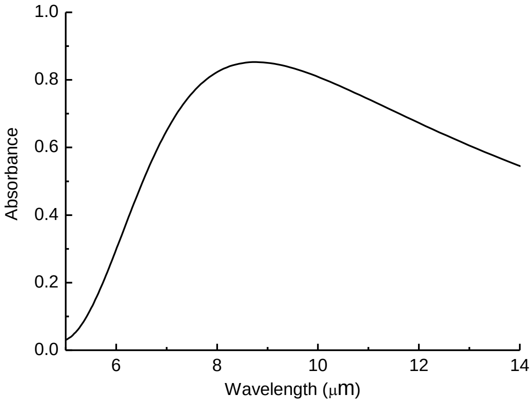

Fig. 3. Measured infrared absorbance for MDM-like structure.

The scanning electron microscopy (SEM, Quanta 200, FEI Corporation) photos of some of the fabricated linear detector structures are shown in Fig. 4. The first linear array is of 50×50 μm pixels on a 80 μm pitch and the second linear array have pxiels of 50 μm diameter on a 80 μm pitch. These detector structures consist of a series of VO_x pixels each with suspended infrared absorption structure supported by two arms of L shape over cavities etched in the porous silicon layer. The cavity thickness is not necessary obey to the resonance condition, since no reflective layer is required on the cavity surface duo to sufficient infrared absorption of the suspended structure. After measuring the pixel height with surface profiler and taking into account the absorption thickness, the cavity length is believed in the range of 1 to 1.5 microns. It is obvious that the absorption structure simples the fabrication process of the detector structure and show advantages over the conventional VO_x detector.

To measure the optical responsivity, the detector array is mounted on a PCB board which is in a metal vacuum chamber at a pressure of about 0.1 Torr. The vacuum chamber have a Ge window with a transmission spectral band of 8-12 μm. The detector array is exposed to the radiation of a blackbody at a temperature of 500 K through the Ge window with an illuminate distance of 100 mm. A mechanical chopper modulates the radiation at a frequency of 20 Hz and the signal is measured using an EG&G 5209 lock-in amplifier.

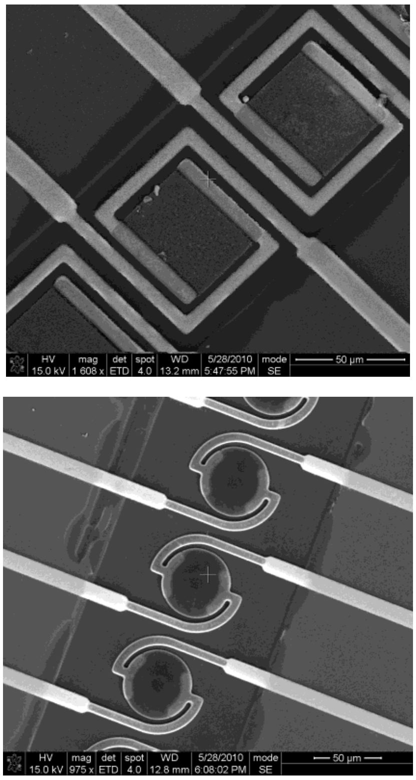

Fig. 4. SEM photos of two kinds of VO_x detector structure.

The results of the responsivity and detectivity D^* dependence on dc bias current are shown in Fig. 5 at a copper frequency of 20 Hz. For this detector, the optimal bias current value is about 18 μA. For this bias current, both average responsivity and the detectivity (D^*) reach maximum value of over 10000 V/W and 6×10^8 $cmHz^{1/2}W^{-1}$, respectively. The detector response time, evaluated based on the response versus frequency characteristic, is about 10 ms. Furthermore, the non-uniformity of the linear array device is less than 10%.

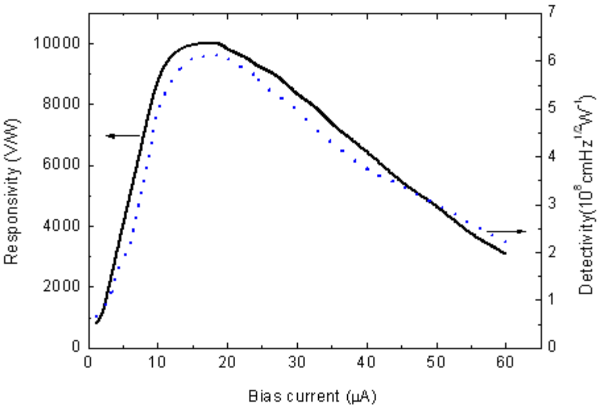

Fig. 5. Average responsivity and detectivity of the VO_x linear array Vs bias current.

In summary, we introduce a novel absorption structure of MDM-like multilayer with thickness no more than 1 μm by using less conducting TiN_x as a surface layer for 128 elements (2×64) VO_x linear detector arrays application. Simulations have shown the multilayer has wide angle response at long-wave infrared band 8-12 μm and the peak absorbance is over 93%. Further simulations reveal that other conducting materials like ITO and highly doped silicon are also have the same properties, and compared with metal surface layer, non-metal conducting materials have wider absorbance and is more suitable for imaging sensor application. Unlike conventional detector array, bolometer with the new absorption layer can decrease the process complexity, and immunity of empty cavity length variation after the sacrifice layer release. Moreover, infrared absorption spectrum can be tuned by changing the dielectric thickness in the MDM-like structure. Since the thin film thickness can be controlled precisely, this function is easily fulfilled.

Acknowledgments

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