Figures of merit and optimization of a VO$_2$ microbolometer with strong electrothermal feedback

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Abstract. The influence of electrothermal feedback and hysteresis on the operation conditions, noise, and performance of a VO$_2$ transition-edge microbolometer has been evaluated. The material undergoes a first-order semiconductor-to-metal phase transition (SMT) within the temperature range $40 < T < 70$ °C. Due to electrothermal feedback, all device parameters, including the required heat-sink temperature, output voltage and current response, response time, linear dynamic range, responsivity, noise, and detectivity, display complex and nonlinear variations with temperature, electrical biasing conditions, input radiation levels, and hysteresis width. In the constant-current mode, the device responsivity extends over a broad temperature range, but under constant-voltage operation it is sharply localized and restricted to the SMT center. Film quality, as represented by the transition and the hysteresis width and the flicker noise magnitude, crucially affects device performance. In the weak hysteretic case and at low $1/f$ noise levels, the device detectivity improves substantially in both operation modes. The spectral range of the device is largely determined by the optical absorptivity of the VO$_2$ film. For operation within the SMT, it extends well into the far IR wavelength region of the atmospheric window, but is substantially smaller for operation in the semiconducting region. © 2008 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2956386]

Subject terms: thermal sensor; modeling; semiconductor-metal transition; metal-insulator transition; transition edge; microbolometer; vanadium dioxide; electrothermal feedback; hysteresis.

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1 Introduction

Uncooled infrared imaging systems are lightweight, demand low power, and are much less expensive than cooled infrared quantum detectors. However, most present devices operate in the semiconducting phase and thus exhibit low detectivity ($D* < 10^7$ cm Hz$^{1/2}$ W$^{-1}$). Moving the operating point of these devices toward the transition region may increase the detectivity by several orders of magnitude. However, when operated in this region these devices usually exhibit hysteresis, a largely disregarded complex, nonlinear, and history-dependent phenomenon. So far, evaluation of the expected performance of a vanadium dioxide (VO$_2$) transition edge device has not been possible because of the lack of a suited theoretical model. Quite recently, researchers at North Carolina State University have succeeded in making very high-quality VO$_2$ films, almost hysteresis-free, which should allow high detectivity ($D* > 10^8$ cm Hz$^{1/2}$ W$^{-1}$).

Transition-edge microbolometers have attracted renewed attention as sensitive, spectrally broadband radiation-sensing devices. Applications also include fast-responding microcalorimeters for x-ray, γ-ray, and nuclear particle detection, and bolometer mixers. The physical function and optimization of superconducting low- and high-$T_C$ transition-edge devices are now well understood. Instruments showing superior performance have been realized. However, design and operation of superconducting transition-edge devices is technically demanding and expensive, due to the need for cooling and control at cryogenic temperatures. Recently, nonstoichiometric vanadium dioxide and tungsten-doped array configurations, exhibiting improved operation at ambient temperature, have been exploited in the absence of a phase transition, using advanced micromachining technology.

Here, we extend the hysteresis model proposed in Ref. 7 to evaluate the bolometric figures of merit and performance of VO$_2$-based transition edge sensors. VO$_2$-based radiometric sensors can be operated in both the anhysteretic, semiconducting state at lower $T$ and as transition-edge devices within a very fast-switching semiconductor-to-metal solid-state phase transition. The electronic solid-state transition appears slightly above ambient temperature, which substantially simplifies the use of the instrument. Devices can be operated under electrical current or voltage biases ($I_c$ or $V_c$) while maintaining strong electrothermal feedback (ETF) conditions. ETF in transition-edge devices leads to pronounced nonlinear behavior. Such effects are mainly caused by temperature- and bias-dependent Joule heating or cool-
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ing $dI_{V,T}$ of the sensing element, and linked to strong temperature-induced film resistance variations $dR_S$. Quantitatively, ETF is described by the variation of $dI_{V,T}/dR_S$. Thus, for materials that exhibit negative values of the temperature coefficient of resistance (TCR) $\beta$, operation in the constant-current mode (CCM) causes a decrease ($dI = -I\beta R_S dT$) on radiation heating $dT$, and the electrothermal feedback is negative. In contrast the constant-voltage mode (CVM), exhibiting positive ETF, leads to an increase in $dI$ ($dI_{V,T} = +V^2 dT/R_S$).

For polycrystalline and epitaxial VO₂ films, as well as bulk crystals, the semiconductor-to-metal phase transition (SMT) is well established over an extended period, covering a transition temperature range 40 to 70 °C. The physical mechanism and origin of the SMT in VO₂ still appear controversial, but are linked to a delicate, temperature-affected interplay and balance between the electron-electron correlations of a Mott-Hubbard insulator and an ordinary metal.¹ A further yet little explored and interesting feature is the presence of a pronounced negative differential resistance effect in the current-voltage characteristics, induced within the transition region by Joule differential resistance effect in the current-voltage characteristics, ²³ indicating periodically incoming radiation, interacting with the heat-sensitive VO₂ film, leads to the formation of a minor hysteresis loop. The phenomenon is not treated by classical hysteresis models, such as the integral Preisach¹³ and the differential Jiles model,¹⁴ which are both unsuited for hysteresis modeling in the present application.

Accurate device modeling, being essential to identify optimum operation requirements, thus relies on implementation of an appropriately adapted hysteresis model. As a function of operating and biasing conditions, and in the presence of strong electrothermal feedback, the following figures of merit were explored: characteristics of device output signal and responsivity, associated linear dynamic range, response times and frequency range of operation, bolometer noise, and achievable detectivities.

Finally, the present investigation includes an evaluation of the optical absorptivity $\varepsilon$ and associated spectral range for the device under consideration, covering the wavelength range $0.35<\lambda<10$ µm.

## 2 Device Design and Modeling

In this work, a follow-up to earlier reported bolometer performance studies is presented. It refers to both a superconducting high-$T_C$ transition-edge microbolometer¹⁵ and a VO₂-based transition-edge device explored, however, in the absence of electrothermal feedback effects.¹⁰ The design route under consideration comprises a very thin (50- to 100 nm) semitransparent and optically absorbing VO₂ film, deposited onto a square supporting Si membrane of size $1 \times 10^{-2}$ cm² and thickness 1 µm. To maintain mechanical integrity of the device both $G_{eff}$ and $C_{eff}$ must be sufficiently high. Here, the supporting membrane is fully suspended and thermally coupled via a high coupling coefficient $G_{eff}$ to the surrounding, massive Si substrate. It serves as a temperature-controlled heat spreader, mounted on a current-controlled Peltier element. Details of the associated thermal control loop are not further elaborated here. The thermophysical properties of the present device arrangement, defined by $C_{eff}$ and $G_{eff}$, largely originate from the supporting Si membrane.

Temperature adjustment of the operation point within the transition can be achieved by means of a Peltier-element cooler thermoelectric (TEC). Since the transition region is above ambient $T$, the TEC will be operated at low bias in heating mode, and the Si substrate of the VO₂ sensor device attached to the TEC hot plate. Its cold side is connected to an air-blown heat sink, which exhibits a sufficiently large heat capacity. However, for high electrical device biasing under strong electrothermal feedback, thermoelectric cooling would be required to compensate Joule device heating. State-of-the-art TECs provide sufficient cooling capacity. An appropriately designed TEC stabilization system has been reported in Ref. 17, where temperature stability of 2.5 mK has been established. For moderate values of the transition width (4 to 6 K), thermal stability of ±100 mK can be considered sufficient for bolometer operating points within the transition region. In connection with a high-heat-capacity heat sink, an appropriately designed proportional-integral (PI) control circuit for the TEC can be implemented that would fully suppress fast thermal fluctuations that appear in high-rate IR imaging applications.

### 2.1 Electrothermal Response Model

The heat balance equation appropriately describes the physical function of a bolometer. The numerical Simulink simulations included the thermal control loop, implemented with a proportional integral-derivative controller. Thus, easy-to-explore analytical expressions defining the figures of merit are not available for this work. The differential equation has been combined with a previously developed hysteresis model, precisely matched to the $R$-$T$ characteristics of the VO₂ film.¹² The earlier-used thermal device parameters $C_{eff}$ and $G_{eff}$, ascribed to a superconducting Si-membrane transition-edge device¹⁵ have been adopted in the present bolometer design. Briefly, the heat balance equation is expressed as

$$C_{eff} \frac{d(T_S - T_H)}{dt} = (J_{CCM} \text{ or } J_{CVM} \text{ or } J_{CTM})$$

$$- G_{eff}(T_S - T_H) + \varepsilon P_0,$$

where $\varepsilon P_0$ is the absorbed input radiation power, $\varepsilon$ is the optical absorptivity, $T_S$ is the sensor temperature, $T_H$ is the heat-sink temperature, $G_{eff}$ incorporates the coupling coefficient and thermal conductivity from the heat-sensing element to the heat sink, $C_{eff}$ is the thermal energy stored at the device, and $J_{V,T}$ is the Joule power applied by electrical biasing of the device with current $I_b$ or voltage $V_b$. It is given as $J_{CCM} = I_b^2 R_S$ for CCM operation with voltage readout and negative electrothermal feedback, and as $J_{CVM} = V_b^2 / R_S$ for CVM operation, current readout, and positive...
electrothermal feedback. Under very low electrical bias values and absence of ETF, an inherent sensor-specific response time can be defined as \( \tau = C_{\text{eff}}/G_{\text{eff}} \). As is evident from Figs. 2–6 in Sec. 3, the device temperature, biasing conditions, and radiation levels crucially affect device performance and dynamic properties. Under equilibrium conditions, i.e., \( d(T_s-T_h)/dt = 0 \), in the absence of input radiation \( \varepsilon P_o \), the actual sensor temperature \( T_s \) is determined by \( G_{\text{eff}} \); the applied Joule biasing power \( J_{\text{CCM,CVM}} \) and adjusted heat sink temperature \( T_h \) according to

\[
T_s = \frac{J_{\text{CCM,CVM}}}{G_{\text{eff}}} + T_h.
\]

\[ (2) \]

### 2.2 Electrical Biasing Conditions

To avoid thermal instability under conditions of positive ETF, bias levels must not exceed a critical value \( V_b \). According to Ref. 18 the critical voltage for simple negative temperature coefficient (NTC) thermistor materials like Ge can be written as \( V_b^2 = -G_{R_0}/\beta \). At higher bias voltages, thermal runaway usually occurs, along with device destruction. However, the simplified model does not apply for transitions-edge devices, where \( R_0 \) and \( \beta \) are not constant quantities, but vary strongly with temperature. \( V_b \) also is affected by the presence of minor-loop hysteresis, and decreases with increasing radiation magnitude. Simulation runs indicated the appearance of an instability at \( V_b > 1.3 \) V. The critical bias voltage thus has been limited to a 10%–lower value, to maintain operation under safe conditions. However, it is important to note that the simulations did not display destructive thermal runaway above the critical voltage, but a rapid increase in the signal noise figure, along with unpredictable responsivity variations. This somewhat unexpected effect of self-stabilization under positive ETF in transition-edge devices will be described elsewhere. \(^{19} \) The bias current \( I_b \) under conditions of negative ETF has been arbitrarily limited to 2.1 mA, mainly to avoid excessive cooling of the heat sink far below ambient temperature.

### 2.3 VO\(_2\) Hysteresis Model

Briefly, the purely algebraic so-called limiting loop (L^2P) hysteresis model comprises a set of four adjustable parameters to fully describe a hysteretic transition. \(^{20} \) It includes the behavior of major, minor, and nested loops, as well as the loop accommodation process. This phenomenon is particularly important for accurate bolometer simulation. To reduce the processing time for the lengthy calculations, minor-loop accommodation was terminated after 10 cycles. The hysteretic variation of the VO\(_2\) film resistance as a function of temperature, \( R_s(T_s) \), can be expressed in an algebraic form as

\[
R_s(T_s) = 17 \exp \left( \frac{2553}{T_s + 273} \right) g(T_s) + 140,
\]

where

\[ (3) \]

\[
g(T_s) = \frac{1}{2} \left( 1 + \tanh \frac{T_s - T_C}{\beta} \right) \left( T_s + T_{pr} P \left( \frac{T_s - T_C}{T_{pr}} \right) \right)
\]

\[ (4) \]

and

\[
T_{pr} = \frac{V_b^2}{2} + T_C - \frac{1}{\beta} \arctanh(2g_r - 1) - T_r,
\]

\[ (5) \]

with

\[
\delta = \text{sign} \left( \frac{dT_s}{dt} \right)
\]

\[ (6) \]

denoting the sign function that defines the polarity of the rate of the temperature variation, applied to the film. The temperature \( T_{pr} \) is the proximity temperature at the start of a new branch, and \( P(x) \) is the proximity function, with \( x = (T_s-T_C)/T_{pr} \), defined by

\[
P(x) = \frac{1}{2}(1 - \sin \gamma x)\left[ 1 + \tanh(\pi x - 2\pi x) \right].
\]

\[ (7) \]

### 2.4 Noise Model

The sensor noise is crucially affected by bias conditions, temperature, and operation frequency and determines the achievable sensor detectivity \( D^* \). The crucial device figure of merit is defined as \( D_{\text{v,j}} = F^{1/2} S_{\text{v,j}}/\langle \delta V_{\text{tot}}^2 \rangle \). Noise modeling has been performed, adopting the same model with refined parameters that was reported earlier in detail in Ref. 21 for the superconducting high-\( T_C \) transition-edge microbolometer. Briefly, four individual contributions, \( \langle \delta V_{\text{tot}}^N \rangle \) and \( \langle \delta V_{\text{tot}}^L \rangle \), constitute the total device noise voltage \( \langle \delta V_{\text{tot}}^2 \rangle = (\Sigma_{\text{v,j}} \langle \delta V_{\text{v,j}}^2 \rangle)^{1/2} \) in the CCM, as

\[
\langle \delta V_{\text{tot}}^N \rangle = \left( \frac{4k_B T_C R_C}{\eta} + \frac{S_{\text{v,j}}^2 S_{\text{f,j}}}{k_B T_B} \right) \left( 1 + \frac{S_{\text{v,j}}^2}{4k_B T_B} + \frac{S_{\text{f,j}}^2}{k_B T_B} \right)^{1/2}.
\]

\[ (8) \]

and the total current noise \( \langle \delta I_{\text{tot}}^N \rangle = (\Sigma_{\text{v,j}} \langle \delta I_{\text{v,j}}^2 \rangle)^{1/2} \) in the CVM is likewise

\[
\langle \delta I_{\text{tot}}^N \rangle = \left( \frac{4k_B T_C}{R_C} + \frac{S_{\text{v,j}}^2 S_{\text{f,j}}}{k_B T_B} \right) \left( 1 + \frac{S_{\text{v,j}}^2}{4k_B T_B} + \frac{S_{\text{f,j}}^2}{k_B T_B} \right)^{1/2}.
\]

\[ (9) \]

The individual noise contributions are called, in order, the frequency-independent resistance (Johnson) noise; the background radiation (photon) noise; the thermal fluctuation (phonon) noise induced by thermal contact and exchange with the heat sink; and finally the frequency-varying (flicker) \( 1/f \) noise. Both photon and phonon noise scale with the frequency-dependent sensor responsivity.
To quantify the dominating 1/f noise contribution for VO₂ films, we here use the approach described earlier in Ref. 22. There are no experimental data available on the Hooge coefficient of VO₂ films, commonly required to quantify the 1/f noise contribution. Thus, the flicker noise expression has been replaced with an empirical formula, including an experimentally determined noise scaling factor $K_N$ that varies over 4 orders of magnitude from $3.2 \times 10^{-18}$ to $2.4 \times 10^{-22}$, similar to the noise-modeling approach from Ref. 23. This quantity crucially depends on the film quality, and scales with the grain size of the VO₂ film. The parameters entering into the noise model are listed in Table 1.

### 2.5 Optical Model

The optical absorptivity $\varepsilon$ has been determined, using the Fresnel equation system in its matrix representation. Real and imaginary refractive index values for VO₂ and Si have been taken from Refs. 24 and 25. Calculations have been performed using optical constants at 300 and 350 K in the purely semiconducting and the SMT state of VO₂, respectively. The geometry corresponds to a bilayer system, comprising a thin VO₂-film at various thicknesses $d$, $0<d<100$ nm, on a 1-μm-thick supporting Si membrane. Calculations were performed at perpendicular radiation incidence, covering the wavelength range $0.35<\lambda<10 \ \mu m$.

### 3 Results and Discussion

Figure 1(a) displays the calculated $R$-$T$ hysteresis curve, matched to the experimentally recorded thermal resistance variation of a thin VO₂ film sputter-deposited onto a Si substrate. The inset shows a pulse train of applied rectangular radiation, and illustrates the related temporal voltage response of the film in the CCM. Associated minor-loop formation and accommodation pertaining to the pulse train are resolved within the descending major loop. Figures 1(a)–1(c) outline the associated variation of the electrical parameters entering into the noise model are listed in Table 1.

#### Table 1 Film parameters and physical constants.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boltzmann constant $k_B$</td>
<td>J/K</td>
<td>$1.38 \times 10^{-23}$</td>
</tr>
<tr>
<td>Stefan-Boltzmann radiation constant $\sigma_B$</td>
<td>W/(cm² K⁴)</td>
<td>$5.67 \times 10^{-12}$</td>
</tr>
<tr>
<td>Background temperature $T_B$</td>
<td>K</td>
<td>300</td>
</tr>
<tr>
<td>Optical absorptivity $\varepsilon$</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Film area $A$</td>
<td>cm²</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Film thickness $h$</td>
<td>cm</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Frequency exponent $n$</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Frequency $f$</td>
<td>s⁻¹</td>
<td>$10^{-1} &lt; f &lt; 10^6$</td>
</tr>
<tr>
<td>$1/f$-noise scaling factor $K_N$</td>
<td>cm³</td>
<td>$3.2 \times 10^{-18}$</td>
</tr>
<tr>
<td>Thermal coupling coefficient $G_{eff}$</td>
<td>W/K</td>
<td>$460 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

![Fig. 1](attachment:figure1.png)

Fig. 1 (a) Variation of VO₂-film resistance as function of $T_S$ within the phase transition. Hysteresis width is set at 6.5 K, total transition width approximately 35 K. The broken line indicates the hysteresis-free limit. Inset illustrates minor-loop formation in the descending branch. Upper right pulse train resembles the thermal input signal; lower left inset shows the voltage response signal due to minor-loop formation. (b) $dR_S/dT_S$ as function of $T_S$ for the descending, ascending, and central branches. (c) The associated $\beta = (1/R_S) \cdot dR_S/dT_S$ as function of $T_S$. 

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VO₂ film parameters $dR_S/dT_S$ and $\beta = (1/R_3) dR_S/dT_S$. The hysteresis width was set to 6.5 K. Pronounced, separated minima are resolved for both $dR_S/dT_S$ and negative values of the TCR, connected to the ascending and descending $R_S(T_S)$ curves. The TCR is $\sim 3\%$ in the semiconducting phase, but increases to $\sim 38\%$ within the transition region. The central broken line indicates the SMT in the absence of hysteresis. Note that the minima from $dR_S/dT_S$ and radiation input, leading to a sharp maximum around $\sim 500\mu$S. In contrast, in the CCM, an almost linear decrease increases weakly from 0.5 to 0.63 ms with increasing bias voltage. In the CVM, the critical bias voltage is limited to $V_s < 1.17$ V. At higher bias values sensor instability is imminent, but is absent for negative ETF conditions of the CCM. The inset to Fig. 2(a) reveals the influence of the accommodation process, which requires $> 30$ cycles for stabilization, revealing a stronger effect in the CVM. Figure 2(b) displays the variation of the heat-sink temperature $T_H$ as a function of bias. In both operation modes, $T_H$ needs to be adjusted below ambient temperature by increasing the bias voltage or current, to secure optimum operation at $T_S$, in accordance with Eq. (2). The ETF effect is much more pronounced in the CCM. The inset to Fig. 2(b) illustrates the linear relation between sensor temperature $T_S$ and heat-sink temperature $T_H$ at low bias current or voltage. Thermoelectric (Peltier) cooling devices, conveniently used to maintain $T_H$, are appropriate for bias currents $\leq 2$ mA.

Figures 3(a)–3(d) illustrate the influence of the radiation input on the device output signal and the related response times. Both device features reveal complex, largely nonlinear variations with the input signal. Figures 3(a) and 3(b) display the characteristics under CCM operation for different current biases. At low radiation levels, the voltage response scales approximately linearly. At higher radiation levels, a shift is observed and smaller slope, until signal saturation appears, attributed to the control circuit. The curve slope and ratio of the respective output signals with radiation power provides the device responsivities $S_{V,I} = d(V_s, I_s)/dP$, representing crucial figures of merit. The linear dynamic range extends up to $8$ mW at high bias current. For low bias and radiation magnitudes, the response time varies weakly, decreases with increasing bias current at low radiation levels, but displays a pronounced maximum at higher radiation input. The displayed device characteristic is substantially different for CVM operation. Here, the current response throughout increases nonlinearly with the radiation level and bias voltage, resulting in a very small linear dynamic range, $< 1$ mW at high bias, but increasing at low applied voltage to about $3$ mW. For very low radiation levels, $\tau$ shows little variation with radiation power and voltage bias. The dynamic response changes drastically with higher bias and radiation input, leading to a sharp maximum around $4$ mW, along with decreasing response times at higher input signals.

Figures 2(a)–4(d) illustrate the effects of operation and biasing conditions on the device responsivities $S_{V,I}$. Figure 4(a) outlines the variation with temperature for both operation modes, using logarithmic scaling. Bolometric response data, obtained at 1-mW radiation input, were calculated from the descending $R_S(T_S)$ curves. Distinct differences between the two modes are resolved, including separated maxima at $320$ K for the CCM with $380$ V/W, and at $334$ K for the CVM with $15$ A/W. The former extended feature approximately follows the inverted $dR_S/dT_S$ curve from Fig. 1(b). It steadily increases toward lower temperature, well into the semiconducting phase. The CVM response characteristics—at substantially lower magnitude—roughly resembles the inverted temperature variation $\beta(T_S)$ of the TCR from Fig. 1(c). The bell-shaped, sharply localized feature is shifted by 14 K to higher $T_S$.

The inset to Fig. 4(b) illustrates the action of the minor-loop accommodation process, being similar to the inset to Fig. 2(a). The associated nonlinear variation of $S_{V,I}$ with biasing conditions is shown in Fig. 4(b). An extended, broad maximum around 1.5 mA bias current is resolved in the CCM. In the CVM, $S_V$ increases steadily with bias voltage, but is limited to 1.17 V to avoid operational instability. Figure 4(c) shows the Bode plots $S_V(f)$ within the range $10^{-1} < f < 10^3$ Hz. Data were taken at low bias current or voltage, in the absence of ETF effects, where the 3-dB rolloff appears at about 600 Hz for both modes. With higher bias currents, it would shift to higher values, due to the reduction of the time constant, in accord with the findings of Fig. 2(a). Figure 4(d) shows the variation of $S_{V,I}$ with hysteresis width $w$, taken as a structural-material quality parameter. The data indicate a substantial device improvement of approximately a factor 4 in the absence of hysteresis of the SMT, while little variation in the responsibility has been found for hysteretic transitions within the range $2 < w < 10\, ^\circ$C.

Figures 5(a)–5(d) illustrate the effects of operation and biasing conditions on the current and voltage noise magnitudes $\langle \delta P^{tot}_I \rangle$ and $\langle \delta V^{tot}_I \rangle$, with 1-Hz bandwidth. Figure 5(a) outlines the variation with temperature, using logarithmic scaling to include both quantities. Both noise figures appear inverted, displaying mirror symmetry around the $T_S$ axis, and the output voltage fluctuations in the CCM substantially exceed the noise magnitude $\langle \delta V^{tot}_I \rangle$ of the CVM. The variation of the noise figures with the biases is shown in Fig. 5(b). In both modes, a nonlinear increase with bias current and voltage is seen. Again, the bias voltage in the CVM is limited to 1.17 V to avoid device instability. Figure 5(c) shows the variation of both noise figures with frequency within the range $10^{-1} < f < 10^3$ Hz with log-log scaling. Both noise figures decline at an identical rate $\propto f^{-1/2}$, indicating a dominating flicker noise contribution. Figure 5(d) shows the corresponding variation of $\langle \delta V \rangle$ with the hysteresis width $w$, taken as a structural-material quality parameter. The data indicate a minor decrease for the CVM towards an anhysteretic characteristic of the SMT, while no variation of the noise figures is resolved within the range $2 < w < 10\, ^\circ$C.

The noise figures $\langle \delta V^{tot}_I \rangle$ within the frequency range $1 < f < 1000$ Hz of a current-biased VO₂ film at the center.
Fig. 2 Variations of (a) response time $\tau$ and (b) heat-sink temperature $T_H$ with biases $I_b$ and $V_b$. The broken line indicates CVM, the solid line CCM operation. Inset to (a) indicates the effect of loop accommodation and stabilization. Inset to (b) illustrates the nearly linear variation of heat-sink temperature $T_H$ with sensor temperature $T_s$, recorded at low bias.
Fig. 3 Variation of device output signals [(a) to (c)] and response times [(b) to (d)], displayed as functions of the input radiation magnitude, under different biasing conditions. The associated slopes $dV_s/dP$ and $dI_s/dP$ provide the responsivity in the CCM and CVM.
Fig. 4 Variation of device responsivities for CCM and CVM, displayed as functions of (a) $T_s$, (b) electrical biases, (c) frequency, and (d) hysteresis width, shown in log scaling. Inset to (b) outlines the influence of the loop accommodation process on sensor responsivity.
Fig. 5 Variations of the total current and voltage noise magnitudes for CCM and CVM, displayed as functions of (a) sensor temperature $T_s$, (b) electrical biases, (c) frequency, and (d) hysteresis width, shown in log scaling.
of the transition at 50 °C and in the semiconducting state at 18 °C can be seen in Fig. 4 of Ref. 16, indicating dominance of 1/f noise in the material. Generally, recorded voltage noise magnitudes are substantially higher in the semiconducting state, in accord with the results of the present noise model. The change of slope of $\langle \delta V_{\text{tot}}^n \rangle$ at $f < 30$ Hz (see Fig. 4 of Ref. 16) in the transition region (50 °C) indicates the presence of a second, yet unidentified noise mechanism, not considered in the present work. A detailed noise analysis of VO₂ films has been reported previously in Ref. 26.

Figures 6(a)–6(d) illustrate the effects of operation and biasing conditions on the device detectivity $D^*_{\text{eff}}$, earlier chosen as a quantitative parameter of device performance. The variation with sensor temperature $T_s$ in Fig. 8(a) shows pronounced maxima, located in both modes at 328 K. Thus, the previously reported peak separation of 14 K in pronouced maxima, located in both modes at 328 K. The variation with sensor temperature $T_s$ in Fig. 8(a) shows pronounced maxima, located in both modes at 328 K. The variation with sensor temperature $T_s$ in Fig. 8(a) shows pronounced maxima, located in both modes at 328 K. Thus, the previously reported peak separation of 14 K in the CCM within the transition region, the advantage disappears for operation in the semiconducting phase, where device detectivities are almost identical, and substantially lower for both modes. The effect of the biases $I_b$ and $V_s$ on the device performance is shown in Fig. 6(b). A steady degradation appears in the CCM with increasing bias current, similar to the result of Fig. 2(a), but is absent in the CVM. At low bias, in the absence of ETF, identical detectivities were found. The influence of operating frequency is shown in Fig. 6(c), where pronounced maxima at 300 Hz are resolved. The rapid device degradation towards lower frequency is due to the detrimental, large contribution of 1/f flicker noise, while the decrease in detectivity with increasing $f$ is attributed to the degrading responsivity curve at high frequency, as seen in Fig. 4(c). Figure 6(d) illustrates the $D^*$ variation with hysteresis width, where towards anhyysteretic conditions a pronounced improvement of almost one order of magnitude is observable for CVM operation. The inset to Fig. 6(b) shows the ratio $D^*/\tau$ for operation in both modes as a function of bias. Due to the decreasing response time in the CCM, as displayed in Fig. 2(a), the associated $D^*$ values remain balanced, leaving almost identical overall device performance for the two modes.

The strong influence of the earlier-mentioned flicker noise on the device performance is shown in Fig. 7, where $D^*$ is plotted as a function of the associated prefactor $K_N$. The analysis reveals that a substantial improvement of $D^*$ of up to $7 \times 10^8$ cm Hz$^{1/2}$ W$^{-1}$ is achievable in the CVM. The associated relation between film quality and $K_N$ is illustrated in the inset to Fig. 7, where experimental findings from Table 1 of Ref. 22 are plotted in logarithmic scaling. A remarkable, sharp increase of $K_N$ and related degradation of device performance is observable with increasing phase transition width of the VO₂-film material. No clear correlation has been identified between hysteresis width and $K_N$.

Finally, Figs. 8(a) and 8(b) illustrate the spectral detection range of the microbolometer for both the center of the SMT at 355 K and the semiconducting state at 300 K, displayed in the inset. The device absorptivity $\varepsilon$ has been obtained at perpendicular radiation incidence. Two cases have been evaluated: placement of the VO₂ film below the Si membrane [Fig. 8(a)] and above the Si membrane [Fig. 8(b)]. In the former case strong oscillatory behavior is found, while in the latter one sees a smooth absorptivity decrease towards longer wavelength. The optical quantity ultimately scales with $D^*$, covering the wavelength range $0.35 < \lambda < 10 \mu m$, and displays pronounced spectral variations. The absorbed radiation transforms into heat, thus changing the film resistance, with the two device materials contributing differently. Since silicon is optically transmitting below its optical band gap, (photon energies <1.05 eV), the thin membrane support accounts for high $\varepsilon$ and $D^*$ values within the visible to near-infrared (NIR) wavelength region, at $0.35 < \lambda < 1 \mu m$. The optical absorption feature extending into the far infrared (FIR) region; thus is attributed primarily to the optical properties of the VO₂ film, being remarkably different in the SMT and the semiconducting phase. The spectral absorption range has been examined here for $\varepsilon \approx 0.2$ at 100-nm VO₂-film thickness. Within the SMT, the spectral range extends into the FIR region up to $\lambda = 6 \mu m$, but is limited to $< 1.3 \mu m$ in the semiconducting phase at 300 K, as illustrated in the inset.

The present device evaluation for a NTC material clearly demonstrates the inverted sensing characteristic of VO₂ films, compared to the earlier-mentioned high-$T_C$ superconducting transition-edge devices, exhibiting positive TCRs. This is immediate from Fig. 1(b) of Ref. 15, where a localized, bell-shaped response curve appears in the CCM with positive ETF, but a substantially extended operation range toward decreasing $T_s$ appears in the CVM, due to negative ETF. Similarly, the sensor dynamics is strongly affected by biasing: with achievable response time $\tau < 10 \mu s$ for the high-$T_C$ transition-edge device under high bias voltages in the CVM from Fig. 1(b) of Ref. 15, the superconducting device provides a much shorter response time than the VO₂ microbolometer. According to Fig. 2(a), at high bias currents of 2 mA, the shortest achievable $\tau$ under strong ETF decreases to 145 $\mu$s. Evidently, the inverted sensor characteristic results from the opposite signs in the TCR for the different materials, which alternate the action of positive versus negative electrothermal feedback.

Substantial differences also appear in the magnitude of achievable device detectivity: experimental high-$T_C$ superconducting transition-edge devices have been reported with $D^*$ values as high as $1.6 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ under positive ETF and at low operation frequency in Ref. 4. For low-$T_C$ devices, $D^*$ even may increase up to $10^{18}$ cm Hz$^{1/2}$ W$^{-1}$. In contrast, as visible from Fig. 7, attainable $D^*$ values for VO₂ in the present design, at moderate noise magnitudes, would remain $< 1 \times 10^8$ cm Hz$^{1/2}$ W$^{-1}$. This quantity remains well within the limits known for other noncooled thermal detectors, including high-$T_C$ microbolometers based on yttrium barium copper oxide, operated far from the phase transition. The reduced performance of the VO₂-microbolometer compared to the superconducting devices primarily originates from the much higher operating temperature (330 versus 90 K), which leads to substantially higher resistance (Johnson) and phonon noise contributions, scaling with $T_C$ and $T_C^*$, respectively. Experimental bolometer matrices reported in Ref. 22 compare well with the present analysis, with $D^* \approx 5 \times 10^7$ cm Hz$^{1/2}$ W$^{-1}$ for $K_N = 4.4 \times 10^{20}$ cm$^{-3}$, obtained in the CCM.
Fig. 6 Variations of device detectivities $D^*$ for CCM and CVM, displayed as functions of (a) $T_S$, (b) electrical biases, (c) frequency, and (d) hysteresis width, shown in log scaling. Inset to (b) illustrates the overall detectivity $D^*/r$ as a function of electrical biases.
Experimental 32 × 32 two-leg-suspended microbolometer arrays have been reported in Ref. 28, employing non-stoichiometric VO₂ films. The devices were operated in the CVM, in the absence of a clear SMT phase transition, attaining moderate $D^*$ of $2.1 \times 10^8$ cm Hz$^{1/2}$ W$^{-1}$ at $\tau=10$ ms, using blackbody 8- to 12-μm wavelength input radiation. Figure 6 of Ref. 28 confirms the simulation results of Fig. 6b of this work, where an increase of $D^*$ with the bias voltage is predicted for CVM operation. Micromachined bolometer devices reported in Ref. 5, with a similar design and in the absence of an SMT, yielded somewhat lower performance, $D^*$ of $1.1 \times 10^7$ cm Hz$^{1/2}$ W$^{-1}$, at low bias currents, with $\tau=0.723$ ms. An alloyed vanadium-tungsten oxide film served as the sensing material, deposited onto Si$_x$N$_y$ membranes. Electrical recordings were taken in the CCM, using optical input by the FIR radiation of a CO₂ laser at 10.6-μm wavelength. To maintain optical absorption in the FIR region, an additional NiCr film was used in the design. ETF effects were not considered in the device evaluations.

As illustrated before, the performance of VO₂ microbolometer devices can be substantially improved by optimal selection of electrical biasing conditions and selected mode of operation, sensor and heat-sink temperature, frequency range, and the VO₂ film material with regard to optical and noise properties. Virtually all results indicate CVM superior to CCM operation; an increase of 30% in $D^*$ is seen in Fig. 6a. This figure also illustrates that high performance in either mode requires setting $T_S=326$ to 328 K. Comparison with Fig. 4(a) shows that the best operation temperature for optimum $D^*$ does not exactly agree with $T_S$ for the highest responsivity. Therefore, achievement of the optimum $T_S$ would require control of $T_H$, most easily achieved with thermoelectric cooling devices.

An important requirement, particularly for the signal readout circuitry, is the increase of $D^*$ with bias voltage in the CVM [Fig. 6b], which would allow use of the full instrumental dynamic range without performance degradation. Since the CCM displays the opposite characteristic, high $D^*$ values for current-biased sensors are only established at low bias, thus limiting the dynamic range. The frequency characteristics of dominating flicker noise crucially affect the variation of $D^*$ with frequency [Fig. 6c]. The large noise contribution at low $f$ in both modes displaces the maximum of $D^*$ towards high frequencies. Therefore, reticulation at around 300 Hz in both modes would be required to establish optimum performance. Reducing the 1/$f$ noise contribution thus is an efficient approach to improve device performance at frequencies compatible with video frame rates. As outlined before, recent improvements of VO₂ film deposition methods are suited to substantially reduce flicker noise contributions. A phase transition broadening $\Delta T_B$ of around 25 °C has been achieved recently$^{29}$ for annealed polycrystalline VO₂ films, rf-reactively sputtered onto float glass. In Ref. 1, a $\Delta T_B$ value as low as 15 °C for single-crystalline, pulsed-laser-
Fig. 8 Variation of the optical device absorptivity \( \varepsilon \) at 355 K within the SMT, displayed as a function of wavelength: (a) air-Si–VO\(_2\) configuration; (b) air-VO\(_2\)–Si configuration. Data were obtained at perpendicular incidence \( D_\perp \), calculated for a range of VO\(_2\) film thickness \( 0 < h < 100 \) nm. Inset displays \( \varepsilon \) for 300 K in the semiconducting state.
deposited (LPD) films on sapphire (0001) substrates has been reported. In view of the $K_T\Delta T_g$ relationship shown in the inset of Fig. 7, flicker noise prefactors of $5 \times 10^{-21}$ and $6 \times 10^{-23}$ thus are achievable with optimized film deposition methods, which would lead to $D^*$ values of $3 \times 10^8$ cm Hz$^{-1/2}$ W$^{-1}$ for polycrystalline and up to $1 \times 10^9$ cm Hz$^{-1/2}$ W$^{-1}$ for epitaxial VO$_2$ films.

The calculated optical absorptivity $\varepsilon$ of Fig. 8 is in agreement with recent experimental findings of Ref. 29, where optical transmission data on VO$_2$ in the semiconducting and the SMT region were reported. Reduced spectral transmission and associated higher absorptivity have been observed in the SMT at 70 °C, covering the wavelength range $\lambda < 2.5 \mu m$. Although $\varepsilon$ extends considerably into the FIR region ($10 \mu m$), its magnitude ($\varepsilon < 0.2$) remains rather low. Hence, to establish improved performance and detectivity, extending into the FIR region at wavelength $\gg 10 \mu m$, use of a highly absorbing, spectrally broadband absorber film, additionally deposited onto the heat-sensing VO$_2$, is essential. Here, use of efficient metallic absorber films, like gold black and ultralow silver (silver black), would be beneficial. These specially prepared materials exhibit very high absorptivity, which extends well into the long-wavelength (terahertz) regime up to 100 $\mu m$, and offer good adhesion to Si substrates.

In conclusion, the optical performance and crucial figures of merit of a hysteretic VO$_2$-based transition-edge microbolometer have been evaluated for constant current (CCM) and constant voltage (CVM) modes of operation. The analysis reveals an approximately factor-3 improved $D^*$ value at the SMT, compared to the semiconducting regime. This ultimately suggests temperature-controlled device operation, with the use of a well-designed heat sink. Neither phase-transition hysteresis nor minor-loop accommodation deteriorates device operation. Strong electrothermal feedback leads to a highly nonlinear detector characteristic, along with pronounced differences between the two modes. The CVM consistently yields higher $D^*$ values than the CCM, at the cost of a reduced linear dynamic range with regard to the incoming radiation level, which is substantially larger in the CCM. This mode exhibits a shorter response time at high bias current, at the cost of a pronounced degradation of the associated $D^*$. Both high detectivity at high bias voltage and limitation to low radiation levels suggest use of the CVM for imaging applications. The CCM would be beneficial for measurements at high radiation magnitudes, in connection with short response times or high-frequency operation, as in laser-beam profiling and characterization, or Fourier transform infrared (FTIR) spectroscopy.

For epitaxial, high-quality VO$_2$ films on sapphire substrates, very low flicker noise levels can be established, so that achievable $D^*$ values approach those of superconducting high-$T_c$ transition-edge devices operated around 90 K. Achievable response times of VO$_2$-based transition-edge devices under conditions of strong negative ETF (CCM) substantially exceed those of superconducting detectors and exclude their use as fast microcalorimeters for x-ray detection.

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References


Biographies and photographs of authors not available.