Coupled absorption filters for thermal detectors

Yuyan Wang, Benjamin J. Potter, and Joseph J. Talghader

Department of Electrical and Computer Engineering, University of Minnesota 4-174 EE/CSci,
200 Union Street Southeast, Minneapolis, Minnesota 55455

Received February 16, 2006; revised April 4, 2006; accepted April 5, 2006; posted April 25, 2006 (Doc. ID 68137)

A resonant absorption cavity that couples long-wavelength infrared (LWIR) light into a movable plate has been demonstrated for thermal detectors, especially microbolometers. Each device is continuously tunable over 8.7–11.1 μm by using electrostatic actuation with voltages from 0 to 42 V. The width of the resonance is relatively broad, approximately 1.5 μm, to match the large widths of many spectral features in the LWIR. At an actuation voltage of 45 V, the device switches into a broadband mode with an absorption width of 2.83 μm. This latter mode is used to enhance sensitivity in low-light situations in which little spectral information is present. © 2006 Optical Society of America

A particularly useful way to make spectrally sensitive detectors is to embed an active p–n junction between two mirrors of an optical cavity. In this way resonant light is coupled into the cavity and absorbed, while light outside the resonance is rejected. Such devices have been used for telecommunications photodetectors to enhance responsivity at one wavelength while maintaining a short and fast active layer.1,2 Similar cavities have been used in micromachined tunable detectors by Vail et al.3 and Larson et al.4 Traditional Fabry–Perot filters work by transmitting light through the filter, and systems of this type for wavelength selection in telecommunications systems have been demonstrated by Peerlings5 and Irmer et al.6

At first glance, this technique does not appear to be easily compatible with thermal detectors7 because of sensitivity issues. If a thermal detector is placed between two mirrors, it must not be in contact with either mirror so that high thermal isolation can be maintained. Unfortunately, micromachined processes with two gaps are very difficult, particularly when the gap spacing must be maintained to optical tolerances. However, one is not required to have absorption in the central layer of a cavity-coupled detector. Cavities that have absorptive mirrors can produce surprisingly high finesse (although low finesse can be achieved as well, as shown here). In this Letter, we present a fully tunable coupled absorption filter for thermal detectors by using a micromachined weakly absorbing top mirror.

This filter is designed to couple the incident light in one wave band into its own top mirror. This is achieved by making the top mirror both lightly reflecting and absorbing, while the bottom mirror is made highly reflecting with negligible absorption. This design causes the device to reflect away light in all wave bands except those near resonance, where destructive interference between light reflected from the top and bottom mirrors causes light to be coupled into the absorbing layer (i.e., the top mirror). Since a thin metal or other conductive material is almost certain to be used as the lightly absorbing layer, the top mirror will have an electrical resistance associated with it. This resistance will change with temperature, and thus the top mirror serves as a microbolometer in addition to its role as an absorption filter. This device is, to the authors’ knowledge, the most widely and continuously tunable cavity for thermal detection in the long-wavelength infrared (LWIR). In addition, it is potentially compatible with pixel-by-pixel tuning of current uncooled focal plane array (FPA) devices.

Figure 1 shows the basic structure of the device prototype. The IR absorbing material is deposited on the top of the upper plate. Chromium (Cr) was chosen as the absorber because it has the most optimal optical constants for IR absorption and reflection of commonly used metals in microfabrication. An important characteristic of Cr is that it produces a reasonably symmetric resonance with respect to wavelength (although there are other metals that fit this characteristic as well). The bottom mirror is a modified quarter-wave distributed Bragg reflector (DBR) with a peak reflectivity close to 10 μm. The top plate of the device is electrostatically actuated by applying a dc voltage to the top and bottom electrodes to change the air gap of the cavity, which tunes the resonance or finesse. The cavity works in two distinct modes. The first mode is the narrowband reflection–absorption mode. It is achieved by electronically controlling the thickness of the air gap from 4.3 to 6.4 μm. The absorption resonance is continuously tuned through the LWIR window. In this work, a...
relatively broad resonance ($\Delta \lambda \sim 1.5 \mu m$) was used to match the coarse spectral features of many objects in the LWIR (much narrower bands can be designed, if desired). This feature is the key to recognize objects with subtle differences in the emissivity spectrum, which cannot be identified by standard bolometers. The second mode is a broadband IR reflection—absorption mode designed to maximize the amount of thermal light absorbed for situations in which low light levels demand maximum detector sensitivity. In this mode, the actuation voltage pulls the top plate near the bottom mirror, and the optical cavity degenerates to a film stack with a near-zero air gap. The top mirror itself does not touch, but rather the beam supports, so as not to thermally short the device. Although the contact area has not been specifically measured in these structures, practical devices will require a contact area that is small enough not to significantly impact thermal performance. This Letter requires a contact area that is small enough not to significantly impact thermal performance. This Letter describes only a single device, but the design is compatible for use with a readout integrated circuit (ROIC), making the technology array compatible.

As mentioned above, the reflectivity of the top mirror is designed to be fairly low because a highly reflective mirror creates a resonance that is too sharp for most of the spectral features in the LWIR. Sharp resonances would waste useful light energy. It is believed that many combinations of materials for the top mirror are possible, but a good choice for the right reflectivity and time constant is a germanium (Ge) plate coated with a thin layer of Cr on top. The materials for the bottom DBR structure are zinc sulfide (ZnS) and Ge. These materials combine the advantages of desirable optical properties and manufacturing simplicity. An optimization program based on transmission matrix simulations is used to optimize the layer structure. The optimized layer structure is shown in Table 1.

Table 1. Device Layer Structure with Designed Nominal Thicknesses$^{a,b}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>$n^b$</th>
<th>$k^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>1.8 nm</td>
<td>11.8</td>
<td>29.8</td>
</tr>
<tr>
<td>Ge</td>
<td>0.6292 µm</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Air gap</td>
<td>3.7–6.8 µm</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Ge</td>
<td>0.1480 µm</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>ZnS</td>
<td>0.5557 µm</td>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>Ge</td>
<td>0.2456 µm</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>ZnS</td>
<td>0.5997 µm</td>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>Au</td>
<td>0.5 µm</td>
<td>12.24</td>
<td>54.7</td>
</tr>
<tr>
<td>Cr</td>
<td>30.0 nm</td>
<td>11.8</td>
<td>29.8</td>
</tr>
<tr>
<td>Si (substrate)</td>
<td>⋯</td>
<td>3.42</td>
<td>⋯</td>
</tr>
</tbody>
</table>

The displayed spectra down in Figs. 2 and 3 use this layer structure, but note that the simulations include a slight induced curvature of the top mirror to obtain an exact agreement between theory and experiment. Specifically, the simulations were carried out by summing the spectral contributions of each point along the curved mirror with their relative weights determined by using measured interferometric data. This leads to excellent agreement between theory and experiment. (For example, before applying voltage, the radius of curvature of the top plate is approximately 442 µm.)

ports, the structural Ge layer was sputtered, followed by a thin evaporated Cr metal for absorption. The Cr metal was patterned by using lift-off. Next, the Au and Cr films were evaporated along the arms and bonding pad to allow for robust electrical contact to the top plate and actuation. Finally, the devices were released in a diluted buffered oxide etchant and dried with a critical point dryer to prevent stiction.

Four different size structures were fabricated: 120 µm × 120 µm, 100 µm × 100 µm, 50 µm × 50 µm, and 25 µm × 25 µm. Since these devices all have a square geometry, the resistances of their top mirrors were all similar at 35 kΩ at room temperature.

The relative reflectance of the 120 µm × 120 µm prototype was measured by using a Nicolet Magna 750 Fourier transform infrared spectroscopy (FTIR) system with a microscope attachment. The device does not transmit measurable light through the substrate; therefore the absorption is merely 1-R, where $R$ is the reflectance. Our simulation indicated that nearly all light absorption happens within the top Cr layer on the device. During the FTIR measurement, a voltage was applied across the supporting arms and the surrounding electrodes beneath the arms by using a Keithley 230 programmable voltage source. Changing the voltage level shifts the interference peak, enabling continuous tuning. The voltage–wavelength relationship was stable and showed no hysteresis.

Figure 2 shows the relative reflectance spectra (versus a silicon surface) with respect to voltage. Gradually increasing the voltage shifts the interference peak toward shorter wavelengths. From 0 to 42 V, the center of the interference curve continuously shifts from 11.1 to 8.7 µm. During tuning, the FWHM of the spectral resonance remained in the range of 1.32 to 1.73 µm. Applying a voltage higher
than 45 V caused the device support beams to snap down to the substrate, which gave the broadband interference curve centered at 11.3 µm with a FWHM of 2.83 µm. A broadband resonance centered at 11.3 µm is created when the voltage is increased to 45 V.

Fig. 2. (Color online) FTIR measurement of the relative reflectance spectra of a 120 µm x 120 µm size filter. When the applied voltage is varied from 0 to 42 V, the narrowband resonance shifts from 11.1 to 8.7 µm. A broadband resonance centered at 11.3 µm is created when the voltage is increased to 45 V.

Fig. 3. (Color online) Finesse tuning via electrostatic actuation for the device in Fig. 2. The FWHM changes by approximately 87% between the two modes.

In summary, a tunable LWTR coupled-absorption filter for thermal detectors has been demonstrated. The resonance and finesse of the device could be manipulated by using electrostatic actuation over a voltage range of 0 to 45 V. In the narrowband mode, the spectral resonance can be continuously tuned over a wavelength range of 8.7 to 11.3 µm. The finesse difference between the broadband and narrowband modes is 87%. This device should enable the development of pixel-by-pixel tunable uncooled infrared FPAs.

The authors acknowledge support from the Microsystems Technology Office of DARPA and the Army Research Office under contract DAAD19-03-1-0343. The processing was performed at the Nanofabrication Center at the University of Minnesota, which is part of the NSF-sponsored NNIN. Y. Wang’s e-mail address is wyy@ece.umn.edu.

References