A 64-pixel linear thermopile array chip designed for vacuum environment

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Abstract

We report on the development of a 64-pixel high performance linear thermopile array chip designed for vacuum environment based on a silicon nitride membrane as substrate, $Bi_{0.87}Sb_{0.13}$/Sb as thermoelectric materials combination and an Ag-black broadband absorber layer. The array chip was mounted on a ceramic substrate and placed on the socket of a commercial hybrid package with 64 pins. Measurements of the linear array chip in vacuum environment and in absence of an entrance filter delivered a responsivity of 245 V/W, a sensitivity of 166 µVm²/W, a specific detectivity of 1.6×10^9 cmHz$^{1/2}$/W at an electrical resistance of 9 kΩ and a thermal time constant of 150 ms. The pixel-to-pixel cross-talk was reduced to less than 0.4 % due to slits in the membrane between adjacent pixels made by dry etching.

Introduction

Thermopiles are well established as reliable cost-efficient infrared sensors. They belong to the class of thermal detectors, which also includes bolometers, pyroelectric detectors and Golay cells. Thermal detectors are advantageous because of their almost constant broadband response over the infrared spectrum and their operation without cooling. That makes them prime candidates as detectors in infrared spectrometers and spectral radiometers. Thermopiles are especially well suited for this field of application in comparison to the other types of thermal detectors because of the following desirable characteristics. They generate an output voltage that is proportional to the incoming radiation, require neither an electrical bias nor an optical chopper and have negligible 1/f noise. Moreover, they are highly linear over many orders of magnitude in incident infrared power and insensitive to substrate temperature variations, making temperature stabilization dispensable.
Infrared spectrometry, which has been useful for quantitative chemical composition analysis of gases, liquids and solids, becomes more and more important in such key applications as process control, environmental/pollution monitoring, automotive engine exhaust analysis and medical applications. Recent advances in the miniaturization of dispersive infrared spectrometers are closely related to the development of uncooled thermal detector arrays [1] as a key enabling technology for these instruments. Linear thermopile infrared detector arrays were developed by a group at Jet Propulsion Laboratory in Pasadena [2, 3] and used in a miniaturized infrared spectrometer with a wavelength range between 3 and 5.5 µm developed for NASA [1]. They were based on n-type Bi-Te and p-type Bi-Sb-Te thermoelectric materials and showed a detectivity greater than 10^9 cmHz$^{0.5}$/W [2].
We report on the development of a 64-pixel high performance linear thermopile array chip based on n-type $Bi_{0.87}Sb_{0.13}$ and p-type Sb thermoelectric materials [4, 5] designed for vacuum environment provided by the spectrometer. Although this thermoelectric materials combination has not such a high thermoelectric figure of merit as the combination Bi-Te/Bi-Sb-Te, it was selected for the reason of simplicity and technological stability of the deposition process, which is due to the fact that only two instead of three different elements are involved, clearly resulting in cost reduction. Nevertheless, this thermopile array chip shows a high performance comparable to the JPL array chip, which can be attributed to some extent to a careful thermal chip design adjusted to vacuum environment.

Thermal Simulation

Parametric thermal simulation calculations of the thermopile array chip based on stationary and transient finite element analysis (FEA) were performed for different design variants (cf. Fig. 1). The width, distance and number of thermocouple legs as well as the localization of the hot thermopile junctions on the IR receiving membrane were varied in order to optimize the thermopile geometry for maximal device sensitivity with several parameters as constraints including the pixel pitch (0.5 mm), the membrane width (1.5 mm) and the electrical resistance (approximately 10 kΩ).

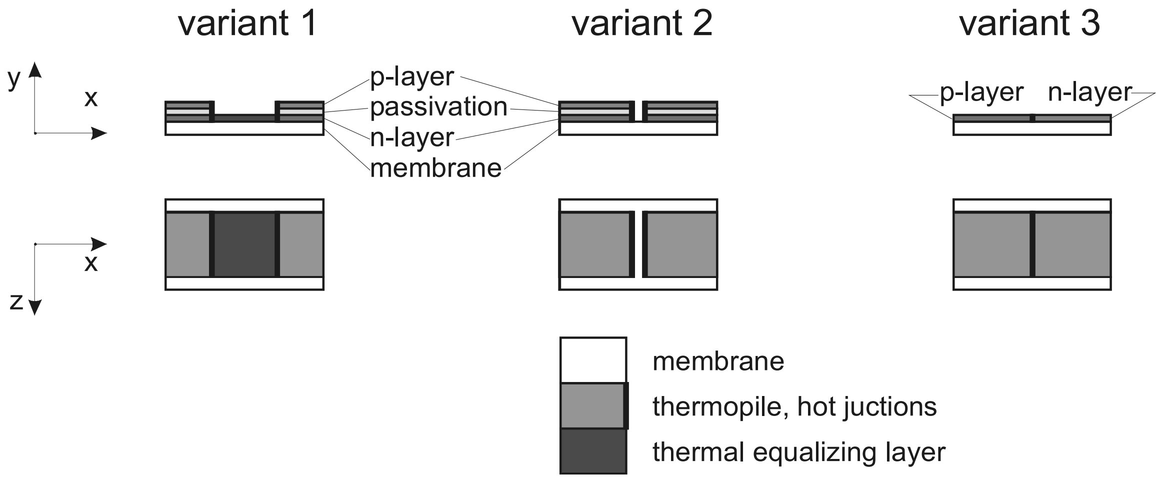

Fig. 1: *Design variants for the pixel setup.*

Fig. 2 shows the FEA modeling region on the membrane of design variant 1. Due to symmetry considerations it comprises a quarter of an irradiated pixel and a half of a neighboring pixel. For the other design variants the FEA modeling region can be constructed in an analogous way. Fig. 3 illustrates a typical stationary temperature distribution of a pixel including the neighboring pixel and the environment (vacuum and – for comparison – air) as a result of finite element thermal simulation for design variant 1.

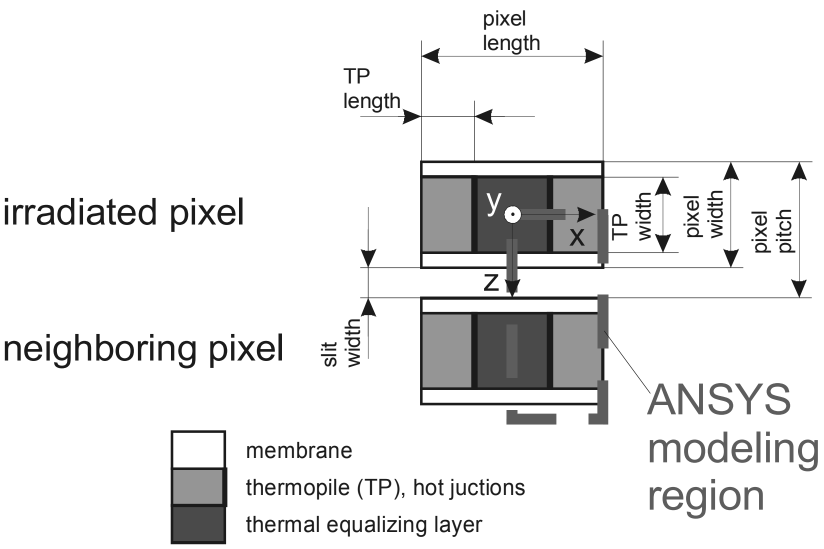

Fig.2: *FEA modeling region on the membrane (design variant 1). The x-direction runs to the heat sink (silicon rim), the z-direction runs to the neighboring pixel, the y-direction runs to the environment. The slit in the membrane between adjacent pixels is introduced for cross-talk suppression.*

As a result of the FEA calculations it was found that design variant 1 is the best one with respect to a high detectivity since the thermopile length is reduced compared to the other design variants resulting in a lower electrical resistance thus improving the noise characteristics. The thermal equalizing layer is crucial in effectively feeding the heat generated by the incident radiation to the hot junctions of the thermopile. The slit in the membrane between adjacent pixels is to minimize thermal cross-talk. The simulation calculations led to the prediction that in vacuum environment a detectivity of about 10^9 cmHz$^{0.5}$/W (or a little more since the estimations of some input parameters were rather conservative) could be obtained with no thermal cross-talk to the adjacent pixels. However, in air environment, the detectivity would be lowered by a factor of about 6 compared to vacuum, the so-called vacuum factor, and there would be a substantial thermal cross-talk of approximately 35 % as illustrated in Fig. 3. The transient thermal simulations predicted a thermal time constant of about 125 ms in vacuum environment.

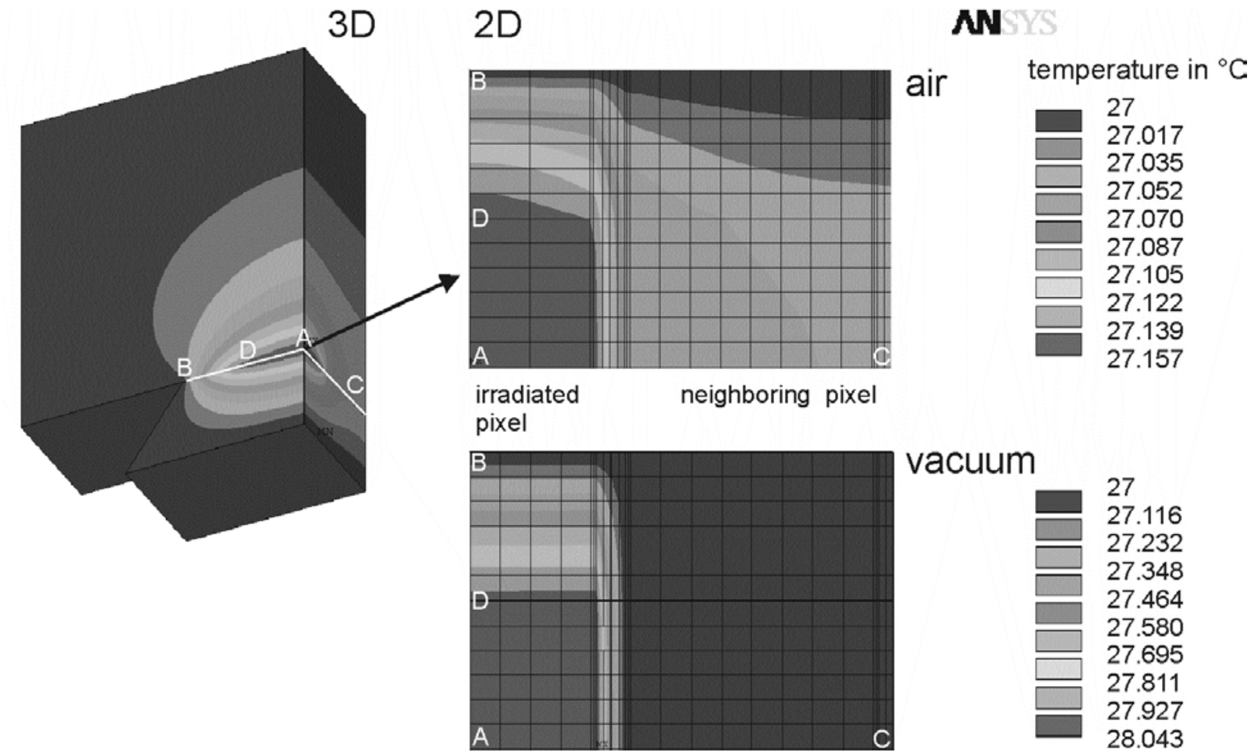

Fig. 3: *Stationary temperature distribution in thermal modeling region of the thermopile array chip at an irradiation load of 38 W/m²; left: 3D distribution including the air environment of the sensor membrane, right 2D distribution on the membrane in air and vacuum environment. The keypoint A refers to the center of the irradiated pixel, the lines A-D-B and A-C refer to the x- and z-directions, respectively. It can be seen that the cross-talk is clearly reduced in vacuum environment.*

Array Chip Characterization

The linear array chip (cf. Fig. 4) was designed based on the simulation calculations of the design variant 1 and realized using micro system technologies employing a silicon nitride membrane as substrate with slits between neighboring pixels made by dry etching, $Bi_{0.87}Sb_{0.13}/Sb$ as thin-film thermoelectric materials combination and a silver-black broadband absorber layer. Details of the thermopile design are illustrated in Fig. 5.

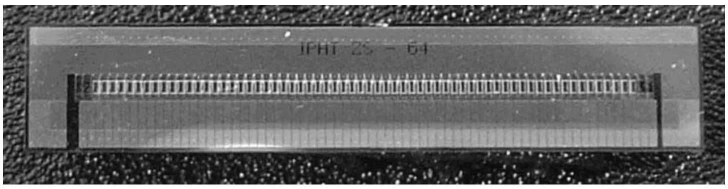

Fig. 4: *Photograph of the 64-pixel linear thermopile array chip (taken before the deposition of the Ag-black layer).*

Measurements (vacuum environment, without filter) of the performance data of the chip delivered the following results: The DC responsivity was 245 V/W, the signal voltage was 6.3 mV at an irradiance of 38 W/m² (500 K black body radiation) resulting in a sensitivity of 166 µVm²/W and the specific detectivity was 1.6×10^9 cmHz$^{1/2}$/W at an electrical resistance of 9 kΩ while the thermal time constant was 150 ms. Since the black absorber layer has a very high absorption over a very broad spectral band of the infrared radiation (cf. Fig. 6) the sensitivity and detectivity is nearly independent on wavelength. The pixel-to-pixel cross-talk was reduced to less than 0.4 % due to the slits in the membrane between adjacent pixels made by dry etching. It was measured by an electrical AC method where the sensing pixel is not loaded by an external radiant flux but by an internal electrical heat power realized by applying an AC voltage to the thermopile. The corresponding electrical circuit is shown in Fig. 7. The AC voltage and current, respectively, is necessary to exclude the Peltier effect, which would falsify the measurement of the electrical heat power when using a DC voltage.

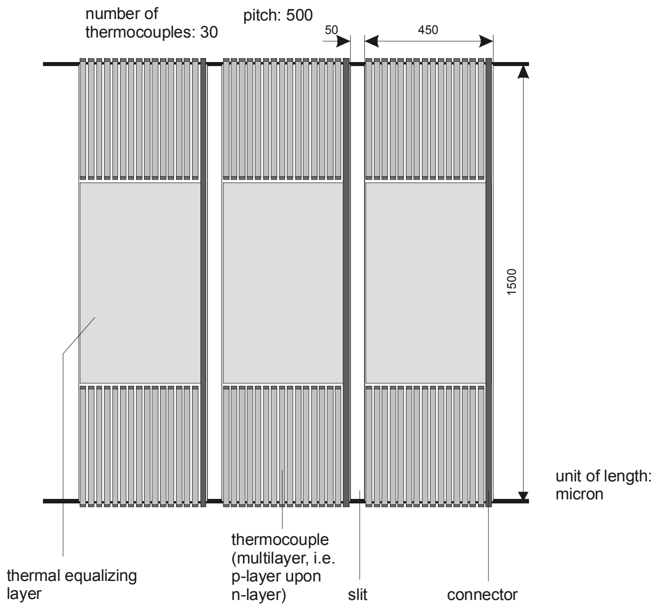

Fig. 5: *Thermopile design of 3 pixels of the 64-pixel array chip, the Ag-black absorber layer (omitted here for clarity) covers the whole pixel of 0.675 mm² size.*

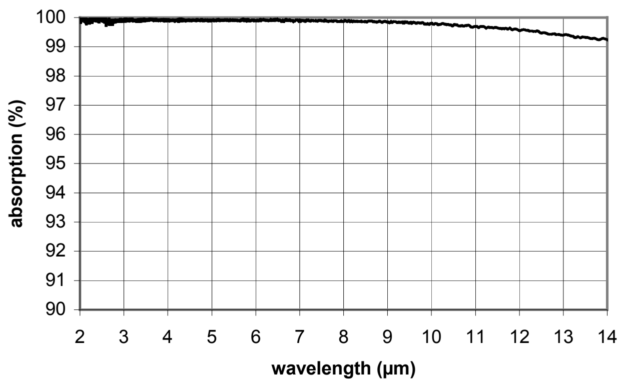

Fig. 6: *Wavelength dependence of the absorption coefficient of a silver-black absorber layer determined by FTIR spectrometry.*

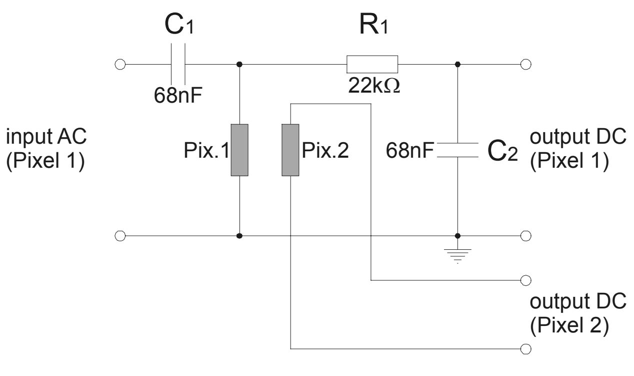

Fig. 7: *Circuit for the measurement of the cross-talk from pixel 1 to pixel 2 by applying an AC input voltage to pixel 1 and measuring the DC output voltage at pixels 1 and the neighboring pixel 2.*

For comparison, measurements in air environment (again without filter) were done resulting in a DC responsivity of 45 V/W, a sensitivity of 30 µVm²/W and a specific detectivity of $3x10^8$ $cmHz^{1/2}/W$. Thus, the vacuum factor was determined to be about 5.5. The thermal time constant was 37 ms. The pixel-to-pixel cross-talk was measured by the AC method to be approximately 28 %.

Assembly

The thermopile linear array chip was mounted on a ceramic substrate and placed on the socket of a commercial hybrid package with 68 pins. In a second version by integrating multiplexers on the socket the number of signal lines was reduced. In this way the use of a smaller 32 pin package was possible (cf. Figs. 8 and 9).

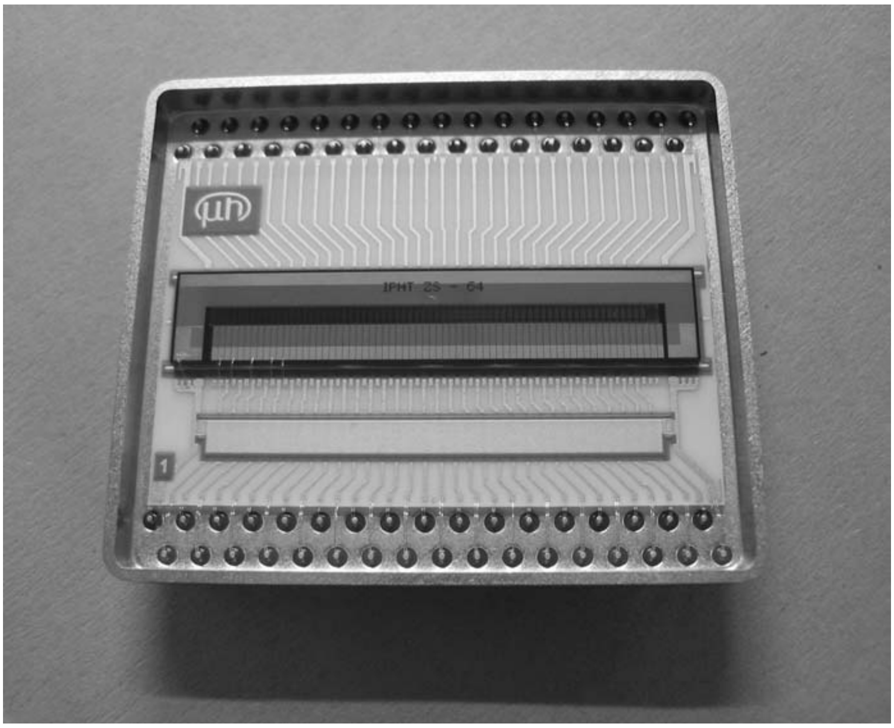

Fig. 8: *64-pixel linear thermopile array chip arranged in a commercial 68 pin hybrid package.*

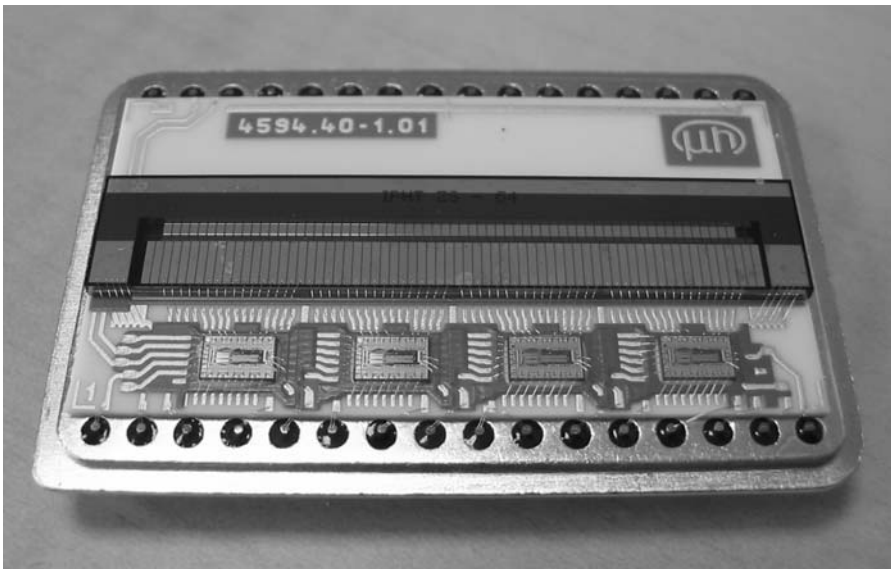

Fig. 9: *64-pixel linear thermopile array chip and multiplexers arranged in a 32 pin hybrid package.*

Fig. 10 shows the principle electronic circuit of the multiplexers inside the hybrid package of the second version. With the help of four 16 channel multiplexers the number of signal lines was reduced from 64 to 4. The position of the selected pixel is determined by the bit pattern on the adress bus.

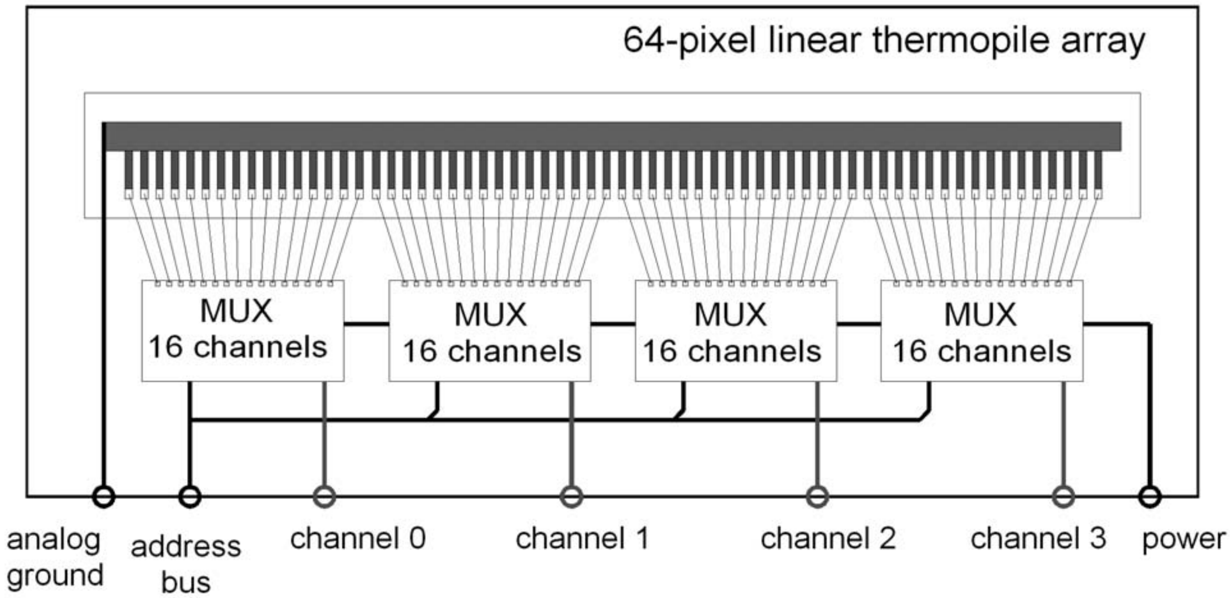

Fig. 10: *Principle electronic circuit of the multiplexers used in the 32 pin hybrid package.*

Conclusion

The new 64-pixel high performance linear thermopile array designed for vacuum environment based on a silicon nitride membrane as substrate, $Bi_{0.87}Sb_{0.13}/Sb$ as thermoelectric materials combination and an Ag-black absorber layer shows a uniformly high detectivity of $1.6x10^9$ $cmHz^{1/2}/W$ in a broad spectral range, which makes it well suited for demanding applications in infrared spectrometry.

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References

[1] J. T. Daly, E. A. Johnson, A. Bodkin, W. A. Stevenson, D. A. White, Proc. SPIE **3953** (2000) 70-87

[2] M. C. Foote, E. W. Jones, T. Caillat, IEEE Transact. Electron Devices **45** (1998) 1896-1902

[3] M. C. Foote, E. W. Jones, Proc. SPIE **3379** (1998) 192-197

[4] F. Völklein, E. Kessler, Thin Solid Films **155** (1987) 197-208

[5] F. Völklein, E. Kessler, Phys. Stat. Sol. (b) **158** (1990) 521-529