Jürgen Müller, Volker Baier, Ulrich Dillner, Rudolf Güttich, Ernst Kessler

A novel micromachined 2x128-element linear themoelectric infrared radiation sensor array

Proceedings of MICRO.tec 2000, VDE World Microtechnologies Congress, Hanover, September 25-27, 2000, VDE Verlag, Berlin, Offenbach, Vol. 1, pp. 465-469

A novel micromachined 2x128-element linear thermoelectric infrared radiation sensor array

Dipl.-Phys. Jürgen Müller, Dipl.-Phys. Volker Baier, Dr. Ulrich Dillner, Dipl.-Phys. Rudolf Güttich, Dr. Ernst Kessler, Institut für Physikalische Hochtechnologie (IPHT) e.V. Jena, Germany

Abstract

As a component for infrared spectrometric analytical instruments a 2x128-element thin-film thermopile linear array sensor with a staggered pixel arrangement was constructed. Contrary to most of the known 1-dimensional and 2-dimensional thermoelectric infrared sensor arrays working all on the base of doped polysilicon, we use the material group Bi-Sb-Te to obtain highest values of thermoelectric efficiency and specific detectivity to realize an optimum of spectral wavelength resolution.

1 Introduction

In principle, it is clear for each expert: Since decades the engineers are using well-known radiation detectors in order to measure radiation power. And they have only to select from two different types: On the one hand, there are the detectors based on photonic effects, and, on the other hand, they can employ the so-called *thermal* detectors, which have a functional layer system for converting the radiation to be measured into heat.

Whereas since long periods especially for military objectives and with an extremely high expense very sophisticated and partially strongly cooled single-element detectors and 1-D or 2-D detector arrays were developed, at present, there is a big renaissance of the *thermal* radiation detectors. This renewed interest in such sensors stems from the potential of microsystem technologies, which has led to far-reaching improvements of their parameters as well as to low-cost batch fabrication. Besides the specific working principle of the *thermal* sensors implies that these sensors respond unselectively to a wide extensive spectral range and do not require any cooling. Therefore, since the middle of the eighties and especially since the middle of the nineties a multitude of promising attempts have been made for creating new uncooled thermal detectors in the shape of resistive bolometers, pyroelectric detectors, ferroelectric bolometers or thermoelectric ("thermopile") detectors [1].

2 Motivation

Our work was focused on a novel multi-element thermoelectric infrared radiation sensor. In thermopile sensors the temperature increase due to the absorbed radiation is converted into an electrical signal by means of the Seebeck effect. As microsensors these devices are of small size and their manufacture is based principally on the concepts of microsystem technologies, e.g., silicon chips, micromachining, selective etching techniques, thin-film deposition methods, specific packaging and interconnection technologies as well as monolithic or hybrid integration of electronic signal processing.

Thermopile linear arrays are 1-D arrangements of a number of pixels comprised by thermopiles. The arrangements of several elements of a size l x w with the length l and the width w are characterized by the pixel number n, the pixel size A (the assembly of thermocouples to a thermopile as a sensitive area) and the pixel pitch p (the distance from a center of a sensitive area to the center of the neighboring pixel). In addition to the single element performance data, i.e. the specific detectivity D^*, the signal voltage V and the time constant τ, the performance of an array is characterized by the cross-talk c to adjacent pixels, too. Essentially, 1-D arrangements are useful as detectors in some important applications: in spectrometers (spectral photometers), in line scanning pyrometers or as sensing element of an earth horizon sensor on satellites. The specific aim of our development should be a low-priced thermopile sensor line for evaluation of far-infrared absorption spectra containing information on vibrational spectra of gases, liquids and solids or of rotational spectra of atoms and molecules of constituents of the atmosphere or other parts of the surroundings. For these spectral regions there are no photonic detectors at favorable prices, hitherto.

3 The state of the art

Table 1 gives a condensed analysis of the state of the art. The first micromachined thermopile-based linear infrared sensing arrays were reported by Choi and Wise [2]. After some refinement they showed the parameters of [7] in an arrangement of two staggered subarrays. Each element of such an array consists of a separate thin membrane spanning a silicon rim. The rim acts always as heat sink and results in a negligible cross-talk. Alternatively to membranes cantilevers were used in [3]. Here a cross-talk of c = 15 % was observed due to heat conduction through the residual air in the sensor housing. Contrary to [2, 3, 5-8, 10-12] where the thermopiles were all fabricated using doped polysilicon, we have used Bi_xSb_{1-x} for the n-type thermopile layer and Sb for the p-type layer already in one of our own former works [4]. These materials show a particularly high efficiency of the thermoelectric conversion characterized by the thermoelectric figure of merit $Z = S^2\sigma\lambda^{-1}$ (S: Seebeck coefficient, σ: electrical conductivity, λ: thermal conductivity), e.g., Z is about $0.5x10^{-3}$ K^{-1} for thin films of $Bi_{.87}Sb_{.13}$. Due to the low thermal conductivity of these films (about 3 $WK^{-1}m^{-1}$) this Z value is nearly one order of magnitude higher than the corresponding one of polysilicon. Therefore, we have realized the new high-resolution linear thermopile array again by materials of the group Bi-Sb-Te.

4 Sensor array design

Whereas the most of the known 1-D and 2-D thermopile arrays [6-9] were especially developed for applications in thermal imaging the task of our latest development was to develop a line-shaped 1-D array on which an infrared spectrum of the length of about 22.5 mm was to be projected. In order to reach a favorable spectral resolution we have striven for a technical solution having as much as possible pixels over the given length of the spectrum. Therefore, we have chosen a number of 256 pixels. The pixels and their arrangement were constructed by means of the micro systems technology: Each pixel consists of a thermopile of several thermocouples built up in a multilayer technology. The thermopiles are arranged on free-standing, stress-compensated SiON membranes. The membranes are formed by anisotropic wet-etching of a 4" silicon wafer from the backside. The thermoelectric material combinations are deposited by vacuum evaporation and magnetron sputtering, resp., and patterned microlithographically. The absorber layer of the pixels is silver black. The whole array is built up in a staggered arrangement of two subarrays of 128 pixels each shifted by half a pitch against each other to reduce the cross-talk. The two subarrays are separated by a narrow bar of bulk silicon. The distance between the membranes of the two subarrays is to be 0.2 mm only. It is favorable to choose an (110)-cut wafer, since here some of the etch-stopping (111) planes are perpendicular to the surface and, hence, vertical walls can be etched by anisotropic etching. A special step to reduce the cross-talk between neighboring pixels was to remove the membrane region between the pixels by reactive ion etching thus creating small slits. Each pixel consists of a thermopile of ten thermocouples of thin-film materials of 0.4 µm thickness having a width of 8 µm each. These parameters and those given by Table 2 are the results of our thermal modeling and extensive simulation calculations [17] by means of 3-D finite element analysis (FEA) using the FEA code ANSYS. We have calculated optimized layouts on the base of two different thermoelectric material combinations: Thin films of 0.4 µm thickness of p-type Sb against n-type $Bi_{.87}Sb_{.13}$ result in a total thermo-e.m.f. of S = 135 µV/K per couple. To get even higher detectivity and responsivity values it is necessary to choose especially high effective thermoelectric materials. Therefore, for the p-type leg $Bi_{.5}Sb_{1.5}Te_3$ was deposited by magnetron sputtering and laser ablation techniques. The deposition was done at elevated temperatures of 300 °C. The transport coefficients of the films were measured without further annealing procedures. However, some problems exist with droplets by the laser technique up to now. We have measured a partial Seebeck coefficient of 172 μVK^{-1} and an electrical conductivity of $\sigma = 5.13x10^4\ \Omega^{-1}m^{-1}$ for the sputtered films and, resp., $S = 224\ \mu VK^{-1}$ and $\sigma = 4.73x10^4\ \Omega^{-1}m^{-1}$ for the laser ablation films. Thus, p-type $Bi_{.5}Sb_{1.5}Te_3$ against n-type $Bi_{.87}Sb_{.13}$ results in these cases in a total thermo-e.m.f. near 300 µV/K. The calculated values and the measured results on real designs are in good agreement [15-18].

With p-$Bi_{.5}Sb_{1.5}Te_3$ as a high efficient thermoelectric material and a slitted membrane between neighboring pixels in a half line, we have obtained a specific detectivity of $D^* = 1.7x10^9$ $cmHz^{1/2}/W$, connected with a thermal time constant τ in the order of 200 ms and a negligible thermal cross-talk c by housing the array in vacuum. It is interesting to establish that the authors of [13, 14] have reached meanwhile in an absolutely independent way from us also parameters of comparable order of magnitude by using very similar technological concepts for manufacturing. By use of xenon as filling gas our values are changed to $D^* = 3x10^8$ $cmHz^{1/2}/W$, τ = 50 ms and c = 37%. Figure 1 shows a 2x128-element array chip.

Ref.	1-D/2-D Number of pixels	Thermo-electric ma-terials	Pixel size A μmxμm Number of couples n	Responsivity V/W	Detectivity cmHz$^{1/2}$/W Cross-talk c	Time constant	Developed at
1986 [2]	1-D 1x8	poly Si:B/Au	400x700 n=40 pitch=500	8.4–12.6	1.6-2.5x10^{7} c=0	5-10	Univ. Michi-gan/USA
1988 [3]	1-D 1x8	p-Si/Al	3000x400 n=5		5x10^{7} c=15 %	180	TU Delft/NL
1992 [4]	1-D$_{stagg}$ 2x8	$Bi_{.87}Sb_{.13}$/Sb	250x2500 n=67	70	3.2x10^{8} c=0	15-20	IPHT Jena/D
1993 [5]	1-D 1x4	p-poly Si/ n-poly Si	400x750 n=12	44	2x10^{7}	18	ETH Zürich/CH
1994 [6]	2-D 128x128	poly Si:B/ poly Si:P	100x100 n=32	1550	~3x10^{7}	1	Def. Agency + NEC Corp./JP
1995 [7]	1-D$_{stagg}$ 2x16	poly Si:P/Au	200x650 pitch=600	64	7.7x10^{7}	10	Univ. Michi-gan/USA
1995 [8]	2-D 32x32	p-poly Si/ n-poly Si	300x300 n=32/36	30		5	Univ. Michi-gan/USA
1995 [9]	1-D 1x128	Constantan/ Chromel	50x50				Honeywell+ Infrared Sol./ USA
1996/7 [10-12]	1-D$_{stagg}$ 2x16	poly Si/Al	440x495 n=40	60	c≤1 %	16	SODERN+ TIMA/F
1998 [13,14]	1-D 1x63	Bi_2Te_3/ $Bi_{.4}Sb_{1.6}Te_{3.6}$	71x1500 n=11 pitch=75	1100	1.4x10^{9} (vac)	99	JET Prop. Lab./USA
1997 [15-19]	**1-D$_{stagg}$ 2x128**	**$Bi_{.87}Sb_{.13}$/Sb $Bi_{.87}Sb_{.13}$/ $Bi_{.5}Sb_{1.5}Te_3$**	**89x600 n=10 pitch=175**	**40 130 1900**	**5x10^{7} (N_2) 2x10^{8} (Xe) 1.7x10^{9} (vac)**	**15 30 200**	**IPHT Jena/D**

Table 1 Thermoelectric multi-element sensors from 1986 to 1998 and the new IPHT array (last row, in bold)

Thermoelectric ma-terial combination	Parameter	Atmosphere in the sensor housing		
		N_2	Xe	vacuum
n-type leg $Bi_{.87}Sb_{.13}$ / p-type leg Sb	V[mV] @ 100 W/m²	0.2	0.7	2.5
	D*[10^{8} cmHz$^{1/2}$/W]	0.5	2	7
	τ [ms]	15	30	90
	cross-talk [%]	47	37	0
	R [kΩ]		17	
n-type leg $Bi_{.87}Sb_{.13}$ / p-type leg $Bi_{.5}Sb_{1.5}Te_3$	V[mV] @ 100 W/m²	0.5	2	10
	D*[10^{8} cmHz$^{1/2}$/W]	0.9	3	17
	τ [ms]	8	30	200
	cross-talk [%]	47	37	0
	R [kΩ]		50	

Table 2 Sensor characteristics

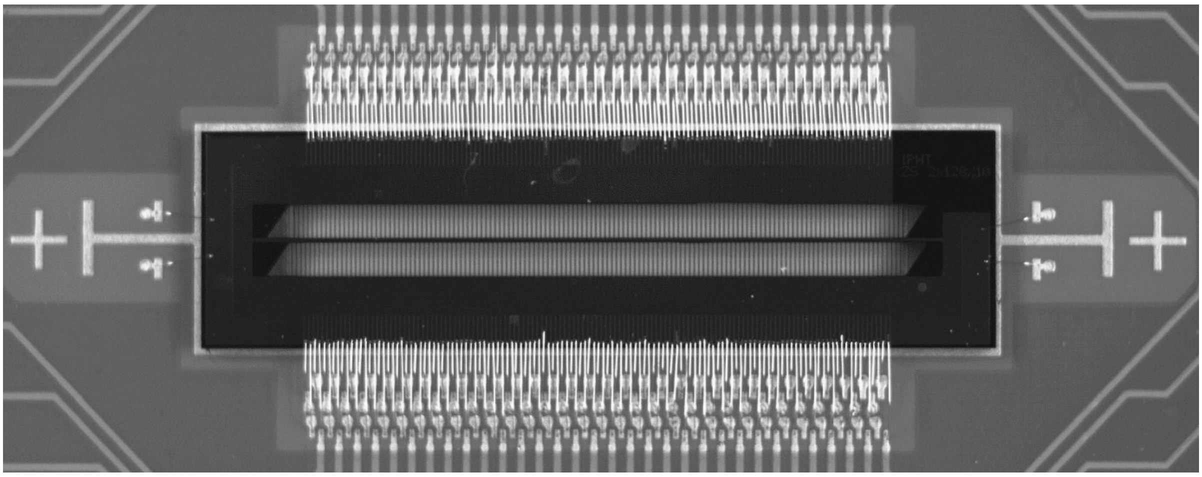

Figure 1 Chip of the new micromachined linear thermopile infrared radiation sensor array with 256 elements arranged in two staggered lines of 128 pixels of 89 µm x 600 µm each

5 Signal processing

The materials applied for use in the sensor chip and the signal processing circuit are not compatible and so the sensor chip and the read-out circuitry cannot be made as a monolithic unit with well-known CMOS manufacturing technologies. This requires to use a hybrid technology for integration sensor chips and electronics to an assembly. In this connection, the special requirements of a housed linear array are: The large number of the pixels of the linear array require a large number of electrical pins of the package or a multiplexed read-out of the pixel signals. The weak signals of the pixels require an amplification. Finally, the thermal management of the hybrid arrangement has to minimize or to homogenize thermal sources in the circuitry. Hence, our arrangement [19] is symmetrically around the sensor chip in the middle of the case and contains eight 16:1-MUX per half line. The 16 MUX are altogether arranged in two floors on ceramic substrates and they are shielded with a ceramic cover to minimize the radiation exchange with the sensor chip. The last 16:1-MUX to switch between the 16 outputs of the MUX inside the housing and finally the OPA for the signal amplification operate outside the case of the thermoelectric IR radiation linear array. The four address lines of the MUX are connected in parallel. The 16 MUX are enabled at the same time. The outputs of the MUX can be read out at the same time. This permits to read out the MUX serial (normal or slow mode) or in the mixed serial/parallel mode (fast mode) with the same clock.

6 Literature

[1] Kruse P.W.: Uncooled IR Focal Plane Arrays, Short Course Notes SC27 AeroSense Orlando 1996, ed. SPIE Bellingham, 1996, pp. 1-149

[2] Choi I.H., Wise A.: A silicon-thermopile-based infrared sensing array for use in automated manufacturing, IEEE Trans. on Electron Devices ED-33 (1986), pp. 72-79

[3] Sarro P.M., Yashiro H., van Herwaarden A.W., Middelhoek S.: An integrated thermal infrared sensing array, Sensors and Actuators 14 (1988), pp. 191-201

[4] Schnelle W., Dillner U., Poser S.: A linear thermopile infrared sensing array, VDI-Berichte 982 (1992), pp. 261-264

[5] Lenggenhager R., Baltes H., Elbel T.: Thermoelectric infrared sensors in CMOS technology, Sensors and Actuators A37-38 (1993), pp. 216-220

[6] Kanno T., Saga M., Matsumoto S., Uchida M., Tsukamoto N., Tanaka A., Itoh S., Nakazato A., Endoh T., Tohyama S., Yamamoto Y., Murashima S., Fujimoto M., Teranishi N.: Uncooled infrared focal plane array having 128x128 thermopile detector elements, Proc. SPIE 2269 (1994), pp. 450-459

[7] Baer W.G., Najafi K., Wise K.D., Toth R.S.: A 32-element micromachined thermal imager with on-chip multiplexing, Sensors and Actuators A48 (1995), pp. 47-54

[8] Oliver A.D., Baer W.G., Wise K.D.: A bulk-micromachined 1024-element uncooled infrared imager, Transducers '95 Digest of Papers, Vol. 2, Stockholm, 1995, pp. 636-639

[9] Wood R.A., Rezachet T.R., Kruse P.W., Schmidt R.N.: IR Snapshot™ Camera, Proc. SPIE 2552 (1995), pp. 654-660

[10] Santos F.V., Bianchi R.A., Karam J.M., Courtois B.: CMOS Compatible IR Sensor Array, Micromechanics Europe Conf. MME'96, Barcelona, 1996

[11] Krebs J.-P.: Un nouveau capteur de terre infrarouge pour petites satellites, Colloque Capteurs pour l'Espace INNOCAP 97, Gre-noble, 20-21 March 1997, pp. 31-40

[12] Krebs J.-P., Brunel O., Guerin C., Guillon D., Niot J.M.: A new infrared static earth sensor for micro and nano-satellites, 2nd Round Table on Micro/Nano Technologies for Space, ESTEC (Noordwijk), 15-17 October 1997

[13] Foote M.C., Jones E.W.: High performance micromachined thermopile arrays, Proc. SPIE 3379 (1998), pp. 192-197

[14] Foote M.C., Jones E.W., Caillat T.: Uncooled thermopile infrared detector linear arrays with detectivity greater than 10^9 $cmHz^{1/2}/W$, IEEE Trans. on Electron Devices ED-45 (1998), pp. 1896-1902

[15] Kessler E., Dillner U., Baier V., Müller J.: A 256 pixel linear thermopile array using materials with high thermoelectric efficiency, Proc. XVI Int. Conf. on Thermoelectrics ICT'97, Dresden, 1997, pp. 734-737

[16] Güttich R., Baier V., Dillner U., Kessler E., Müller J.: Ein Thermopile-Zeilensensor mit 256 Pixeln aus thermoelektrisch hocheffektiven Materialien, Dresdner Beiträge zur Sensorik: 5th Conf. Infrared Sensors and Systems, edited by G. Gerlach, Vol. 4, Dresden University Press, 1997, pp. 71-76

[17] Dillner U., Kessler E., Baier V., Güttich R., Müller J.: Thermal simulation of micromachined linear thermopile infrared radiation sensor arrays, Proc. THERMINIC'97, Cannes, 1997, pp. 221-216

[18] Müller J., Baier V., Dillner U., Güttich R., Kessler E.: *Ein neues 2x128-Pixel-Linear-Array*, VDI-Berichte 1397 (1998), pp. 197-203

[19] Güttich R., Baier V., Dillner U., Kessler E., Müller J., Berger A., Behrendt S., Suphan K.-H.: Thermoelectric IR Radiation Linear Array with Hybrid-Integrated Signal Processing, Proc. SENSOR'99 Vol. 1, Nürnberg, 18-20 May 1999, pp. 29-34