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S.V. PAVLOV, WALDEMAR WÓJCIK, R.L. HOLYAKA,
O.D. AZAROV, S.V. BOHOMOLOV, YANG LONGYIN

ANALYSIS OF DEVELOPMENT STATE OF THE THERMAL FLOW SENSORS OF GENERAL, BIOMEDICAL AND ECOLOGICAL DESIGNATION

Vinnytsia National Technical University, 95, Khmelnitske shosse, 21021, Vinnytsia, Ukraine,
e-mail: psv@vntu.edu.ua
Lublin University of Technology, Poland
Lviv Polytechnic National University, Ukraine

Анотація. В роботі проаналізовано характеристики мікроелектронних сенсорів потоку, що дозволило зробити низку важливих висновків, а саме: сучасні мікроелектронні теплові сенсори потоку, і зокрема сенсори біомедичного призначення, характеризуються значним різноманіттям принципів формування сигналу – від елементарних лінійних перетворювачів на основі одного чутливого елементу і до нелінійних (генераційних, часозалежних) перетворювачів на основі матриць функціонально інтегрованих елементів. Актуальною залишається проблема енергоспоживання теплових сенсорів потоку. Особливо це характерно при живленні сенсорів призначення від автономних, тобто, малогабаритних малопотужних низьковольтних електрохімічних елементів. Зменшення енергоспоживання (потужності та температури нагріву) призводить до виникнення паразитного впливу опорів сигнальних ліній і, як наслідок, до погіршення функціональних характеристик, зокрема, зменшення точності вимірювання швидкості потоку.

Ключові слова: теплові сенсори потоку, сигнальні перетворювачі, інтегральна електроніка біомедичного, екологічного призначення.

Abstract. The paper analyzed the characteristics of microelectronic flow sensors, which made it possible to draw a number of important conclusions, namely: modern microelectronic thermal flow sensors, and in particular biomedical sensors, are characterized by a significant variety of principles of signal formation - from elementary linear converters based on one sensitive element to non-linear ones (generation, time-dependent) converters based on matrices of functionally integrated elements. The problem of energy consumption of thermal flow sensors remains relevant. This is especially characteristic when powering destination sensors from autonomous, i.e., small-sized, low-power, low-voltage electrochemical cells. A decrease in energy consumption (power and heating temperature) leads to the parasitic effect of signal line resistances and, as a result, to the deterioration of functional characteristics, in particular, to a decrease in the accuracy of flow rate measurement.

Keywords: thermal flow sensors, signal converters, integrated biomedical and ecological electronics.

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INTRODUCTION

The development of modern diagnostic devices of biomedical designation is characterized by the rapid widening of physical methods of measuring transformation of functional possibilities, improvement of technical characteristics, wide introduction of microelectronic technologies and microprocessor engineering. These trends are vividly manifested in one of the most important classes of diagnostic equipment –devices for measurement of gasses and fluids flow speed (flow sensors), used for measurement of the respiratory system parameters (in particular, in case of asthmatic diseases), artificial respiration systems, means of biochemical analysis. Besides, flow sensors find wide application in the technological processes of pharmacology and devices used for ecological monitoring.

From the point of view of biochemical compatibility of the materials, high operation reliability, minimal impact on the parameters of the studied flow and the possibility to measure both small and large flows of fluids and g–asses thermal flow sensor (hot-wire anemometer)– devices, measuring ability of which is based on the determination of the temperature field in locally heated substance of the flow have the priority in biomedical equipment [1,2].

1. ANALYSIS OF THE STATE – OF-ART OF THE DEVELOPMENT OF THE THERMAL FLOW SENSORS OF GENERAL AND BIOMEDICAL DESIGNATION

Thermal flow sensor is a device for measurement of liquid or gas flow rate, based on the principle of measurement of the temperature field of the locally heated substance of the flow [1, 2, 3].

Several basic methods of signal formation, stipulated by the flow rate are distinguished. In the simplest method the temperature of the heater, located in the flow is measured – the temperature of the heater decreases with the increase of the flow rate, as a result of heat exchange. More progressive methods imply the local heating of the flow environment and measurement of the temperature difference in the flow in the areas prior to (*S1*) and after (*S2*) the heater in the direction of the flow propagation (Figure 1). This enables, first, to measure not only the flow rate but also its direction and, secondly, minimize the impact of the temperature of the flow substance on the result of the measurement [4, 16, 17].

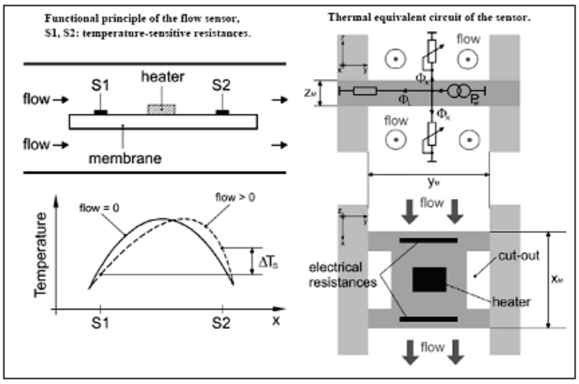


Figure 1 – Structure and the functional principle of microelectronic thermal flow sensors operation

Static and dynamic (Thermal Time-of-Flight Mode Transducers) information signal formation circuits, in particular, as it is shown on the example of biomedical thermal flow sensor with integrated signal converter, are distinguished (Figure 2) [4, 5, 6].

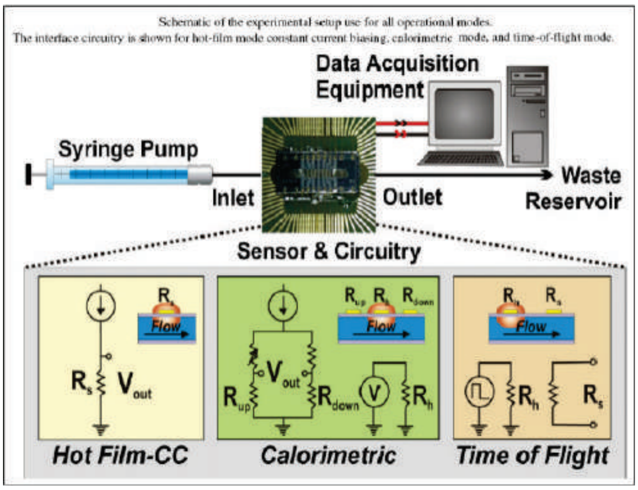


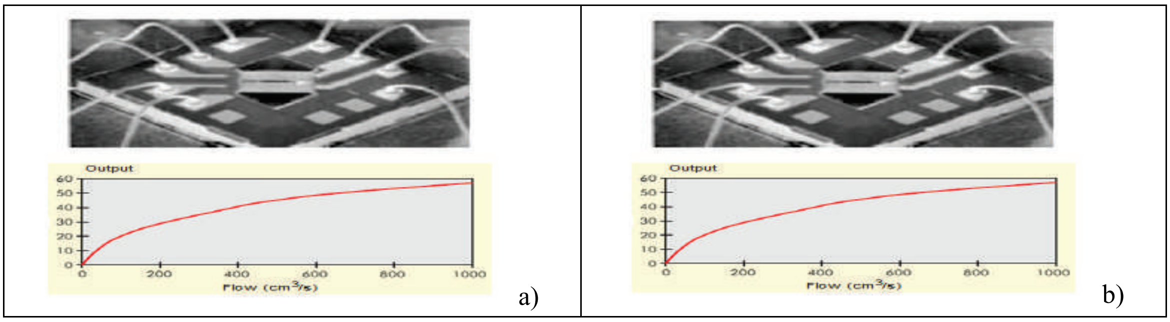
Figure 2 – Principles of signal formation in thermal flow sensors

If it is necessary to measure the large volumes of flows in the main line of a large diameter, the bypass pipe of small diameter (connected in parallel to the main) is formed in it, the flow in this bypass pipe is proportional to the flow in the main line. Measuring the flow rate only in the bypass pipe and approximating the obtained result of the measurement by the flow rate in the main line, the reduction of energy losses for flow heating is achieved and the temperature impact of thermal flowmeter on the flow on the whole [18, 19, 20].

In various functional-structural realizations of the thermal flow sensors their sensors of the temperature difference are combined with the heaters. In such a case, a flow sensor consists of two functionally integrated elements, each of them is heated and, characterized by the known value of the temperature resistance coefficient, provides the possibility of temperature signal formation.

The temperature of the first in the direction of the propagation flow of the functionally integrated element is smaller relative to the second, similar to the dimensions and heating energy element that is stipulated by the heat transfer between these elements of the flow medium. The example of the realization of the microelectronic flow sensor, based on the functionally integrated elements of the thermoresistive type, in particular, model AWP 2100 V – of the world leader in the field of microelectronic sensor electronics, Honeywell company, is shown in Figure 3 [7, 8].

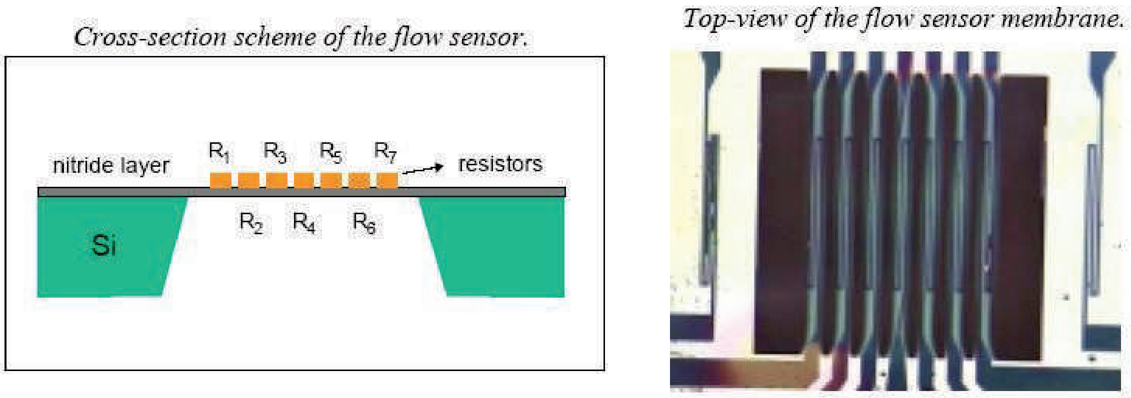
Membrane structure of the sensor, that provides minimal value of heat transfer between functionally integrated elements and the chip of the integrated circuit, is formed by the technology of the silicon MEMS (Micro-Electromechanical – Systems) structures. The dimensions of the flow sensor, based on MEMS structure, typically do not exceed several millimeters whereas the dimensions of the sensing elements (in particular, functionally integrated elements) are of the order 100 microns. Important role in thermal flow sensors Heating mode and mutual location of temperature difference sensors relative to the heater play an important role in thermal flow sensors, this is discussed in [9, 10].



a) b)

Figure 3 – Microelectronic MEMS structure of:
a) thermal flow sensor; b) typical characteristics

New direction in the development of thermal flow sensors is presented by the multiband MEMS flow sensor, based on the matrix of functionally integrated elements [11, 21, 22]. The construction of such a sensor is shown in Figure 4, distribution of the temperature in the elements is shown in Figure 5 and its exterior view – in Figure 6.



a) b)

Figure 4 – Construction of the thermal matrix MEMS flow sensor:
a) cross-section scheme;b) photograph

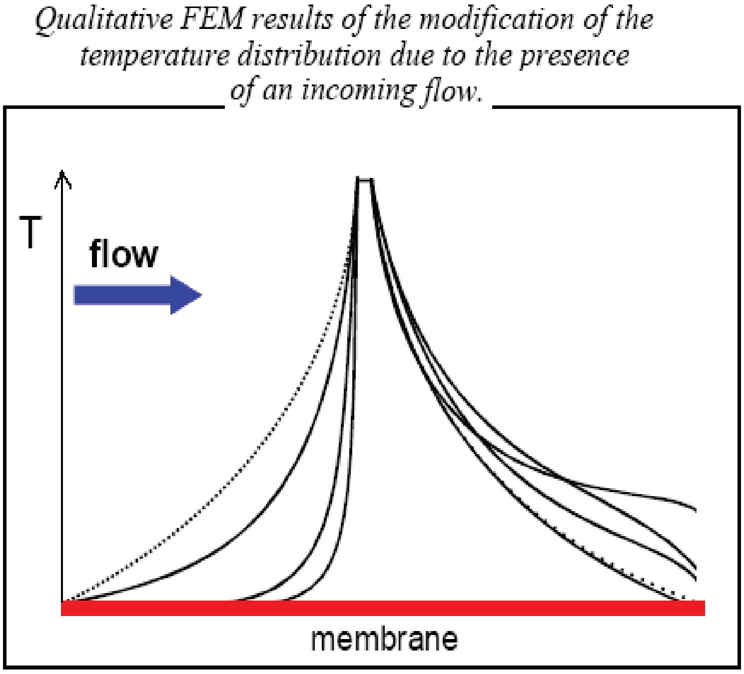
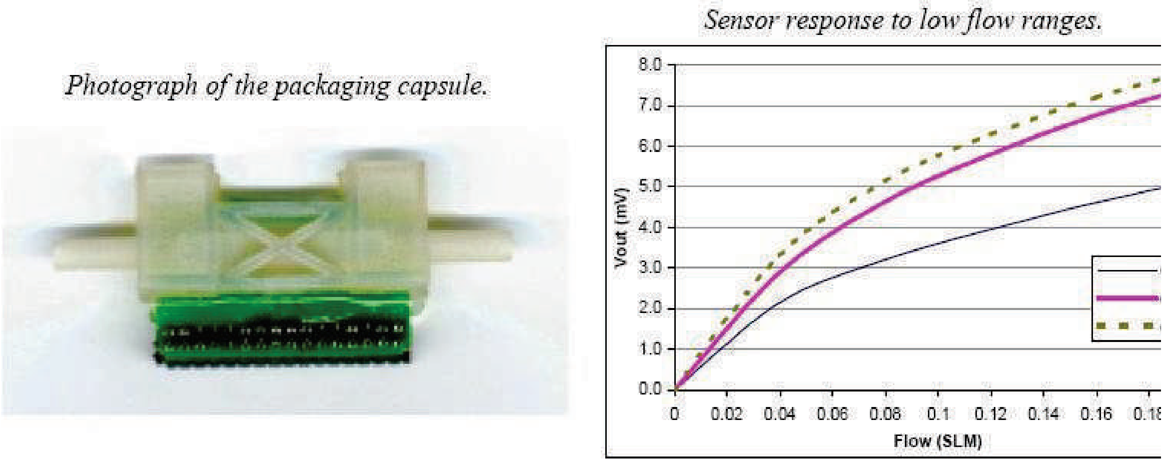


Figure 5 – Temperature distribution in the thermal matrix flow sensor

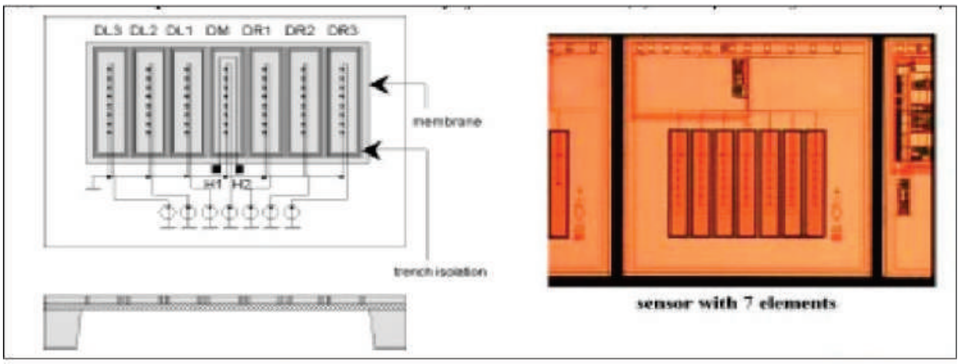


a) b)

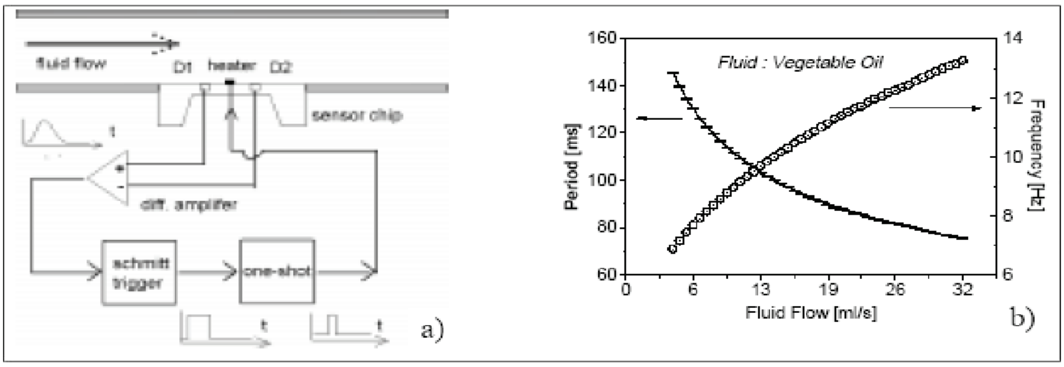
Figure 6 – Thermal matrix flow sensor:
a) photograph; b) example of the functional characteristics

Construction, principle of signal formation and functional characteristics of matrix flow sensors, based on thermal-time-of-flight mode are shown in Figures 7-8, correspondingly [12]. Such method provides further decrease of energy consumption and the possibility of microprocessors signal conversion without the usage of the analog-to-digital converters [23, 24, 25].

Greater part of the thermal flow sensors, considered above, did not get industrial introduction – the given publications demonstrate only the realization of the laboratory prototypes. That is why, to give a more comprehensive vision of the state of art of thermal flow sensors development, we will suggest several examples of the mass production and commercially available devices of such type. They are, in particular, thermal flow sensors, manufactured by the company ELDRIGE PRODUCTS Inc. (Figure 5), hot-wire anemometers A-477 (Figure 10), Testo 405 (Figure 11) and Testo 425 (Figure 12), presented at the market of Ukraine by the Association " Industry-Ukraine" [13, 14]. Sphere of the application – monitoring of the labor conditions in industry, ecology, etc [28, 29, 30].



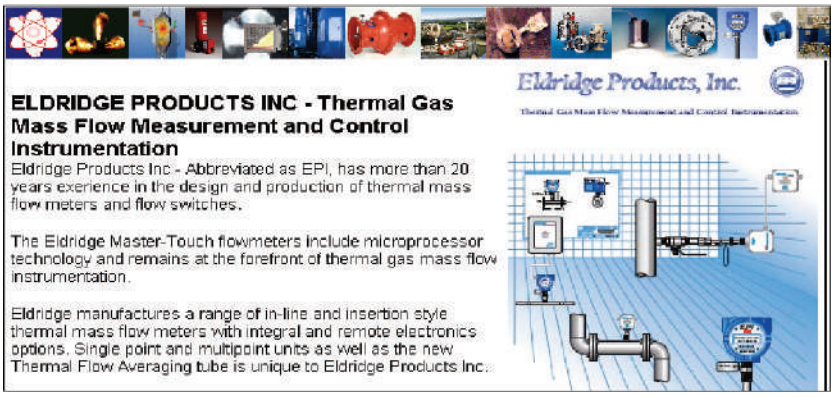
a) b)
Figure 7 – Matrix thermal Time-of-flight mode flow sensor:
a) construction; b) exterior view



a) b)
Figure 8 – Matrix Thermal-Time-of-Flight Mode flow sensor:
a) functional scheme of signal formation; b) characteristics of the conversion

2. TECNOLOGIES FOR REALIZATION OF THERMAL FLOW SENSORS, DEVELOPED FOR BIOMEDICAL AND ECOLOGICAL APPLICATION

We will consider thermal flow sensors, developed for biomedical application. The required information can be found at numerous information resources, they describe, in particular, characteristic features of the devices of biomedical designation, scientific research, devoted to the development of the flow sensor for biomedical application, carried out in Bio-MEMS & Microsystems Laboratories of University of South Florida (Figure 13) [12, 13] and State of Utah Center of Excellence for Biomedical Microfluidics (Figure 14) [14, 31].



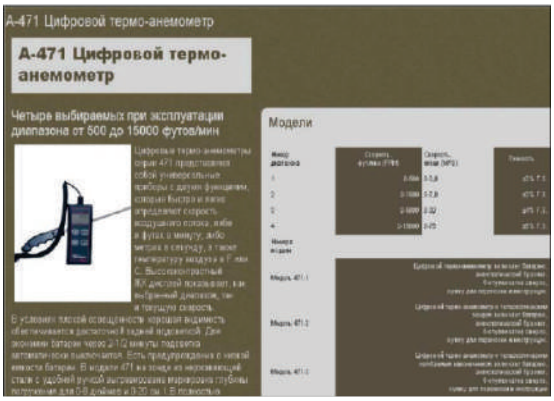
ELDRIDGE PRODUCTS INC - Thermal Gas Mass Flow Measurement and Control Instrumentation

Eldridge Products Inc - Abbreviated as EPI, has more than 20 years exerience in the design and production of thermal mass flow meters and flow switches.

The Eldridge Master-Touch flowmeters include microprocessor technology and remains at the forefront of thermal gas mass flow instrumentation.

Eldridge manufactures a range of in-line and insertion style thermal mass flow meters with integral and remote electronics options. Single point and multipoint units as well as the new Thermal Flow Averaging tube is unique to Eldridge Products Inc.

Figure 9 – Information materials of the Company ELDRIDGE PRODUCTS Inc



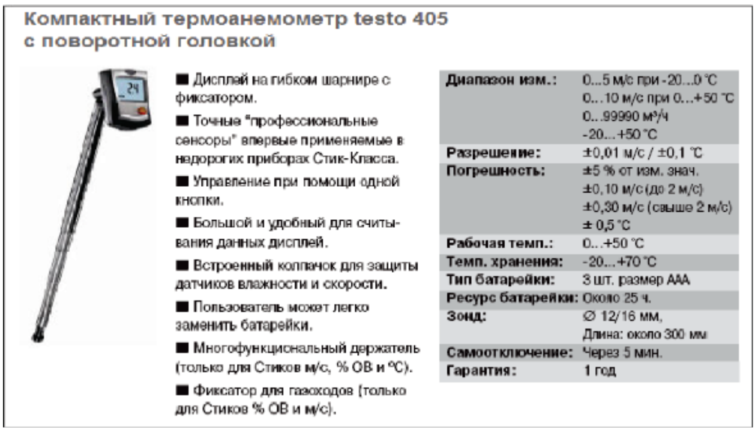
A-471 Цифровой термо-анемометр

А-471 Цифровой термо-анемометр

Четыре выбираемых при эксплуатации диапазона от 600 до 15000 футов/мин

Модели

Figure 10 – Brief characteristics of the hot-wire anemometer A-471

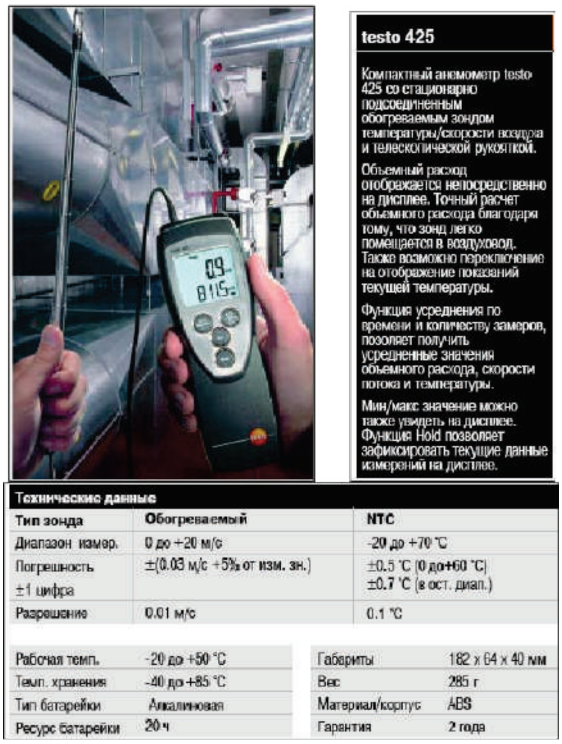


Компактный термоанемометр testo 405 с поворотной головкой

- ■ Дисплей на гибком шарнире с фиксатором.
- ■ Точные "профессиональные сенсоры" впервые применяемые в недорогих приборах Стик-Класса.
- ■ Управление при помощи одной кнопки.
- ■ Большой и удобный для считывания данных дисплей.
- ■ Встроенный колпачок для защиты датчиков влажности и скорости.
- ■ Пользователь может легко заменить батарейки.
- ■ Многофункциональный держатель (только для Стиков м/с, % ОВ и °С).
- ■ Фиксатор для газоходов (только для Стиков % ОВ и м/с).

Диапазон изм.:	0...5 м/с при -20...0 °С 0...10 м/с при 0...+50 °С 0...99990 м³/ч -20...+50 °С
Разрешение:	±0,01 м/с / ±0,1 °С
Погрешность:	±5 % от изм. знач. ±0,10 м/с (до 2 м/с) ±0,30 м/с (свыше 2 м/с) ± 0,5 °С
Рабочая темп.:	0...+50 °С
Темп. хранения:	-20...+70 °С
Тип батарейки:	3 шт. размер ААА
Ресурс батарейки:	Около 25 ч.
Зонд:	∅ 12/16 мм, Длина: около 300 мм
Самоотключение:	Через 5 мин.
Гарантия:	1 год

Figure 11 – Brief information about the hot-wire anemometer Testo 405



testo 425

Компактный анемометр testo 425 со стационарно подсоединенным обогреваемым зондом температуры/скорости воздуха и телескопической рукояткой.

Объемный расход отображается непосредственно на дисплее. Точный расчет объемного расхода благодаря тому, что зонд легко помещается в воздуховод. Также возможно переключение на отображение показаний текущей температуры.

Функция усреднения по времени и количеству замеров, позволяет получить усредненные значения объемного расхода, скорости потока и температуры.

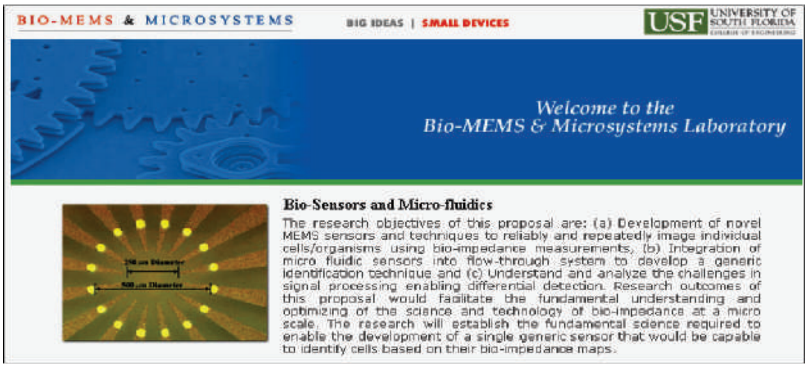
Мин/макс значение можно также увидеть на дисплее. Функция Hold позволяет зафиксировать текущие данные измерений на дисплее.

Технические данные

Тип зонда	**Обогреваемый**	**NTC**
Диапазон измер.	0 до +20 м/с	-20 до +70 °С
Погрешность ±1 цифра	±(0.03 м/с +5% от изм. зн.)	±0.5 °С (0 до+60 °С) ±0.7 °С (в ост. диап.)
Разрешение	0.01 м/с	0.1 °С

Рабочая темп.	-20 до +50 °С	Габариты	182 x 64 x 40 мм
Темп. хранения	-40 до +85 °С	Вес	285 г
Тип батарейки	Алкалиновая	Материал/корпус	ABS
Ресурс батарейки	20 ч	Гарантия	2 года

Figure 12 – Brief information about the hot-wire anemometer Testo 425

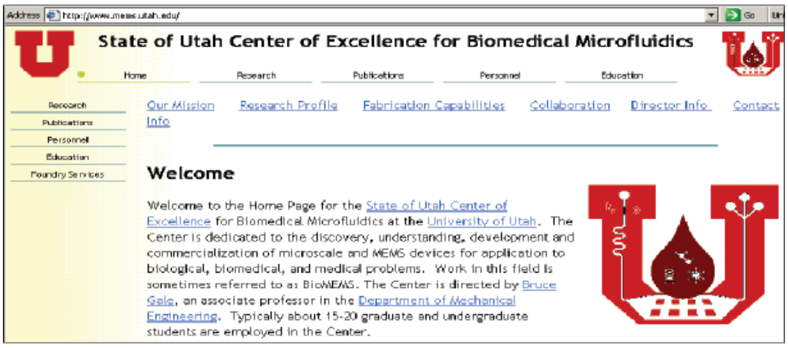


Welcome to the
Bio-MEMS & Microsystems Laboratory

Bio-Sensors and Micro-fluidics

The research objectives of this proposal are: (a) Development of novel MEMS sensors and techniques to reliably and repeatedly image individual cells/organisms using bio-impedance measurements, (b) Integration of micro fluidic sensors into flow-through system to develop a generic identification technique and (c) Understand and analyze the challenges in signal processing enabling differential detection. Research outcomes of this proposal would facilitate the fundamental understanding and optimizing of the science and technology of bio-impedance at a micro scale. The research will establish the fundamental science required to enable the development of a single generic sensor that would be capable to identify cells based on their bio-impedance maps.

Figure 13 – Information resource Bio-MEMS & Microsystems Laboratory of University of South Florida



State of Utah Center of Excellence for Biomedical Microfluidics

Our Mission Info | Research Profile | Fabrication Capabilities | Collaboration | Director Info | Contact

Welcome

Welcome to the Home Page for the State of Utah Center of Excellence for Biomedical Microfluidics at the University of Utah. The Center is dedicated to the discovery, understanding, development and commercialization of microscale and MEMS devices for application to biological, biomedical, and medical problems. Work in this field is sometimes referred to as BioMEMS. The Center is directed by Bruce Gale, an associate professor in the Department of Mechanical Engineering. Typically about 15-20 graduate and undergraduate students are employed in the Center.

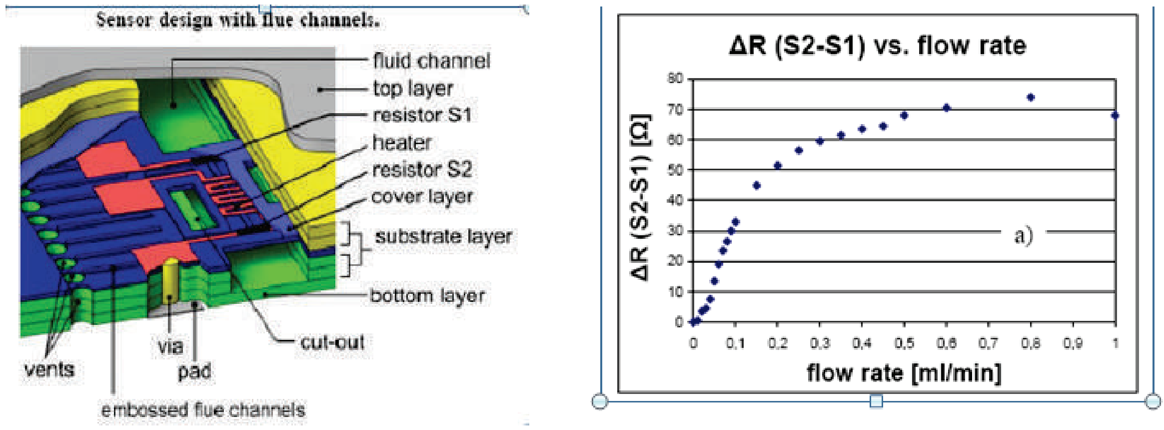
Figure 14 – Information resource of State of Excellence for Biomedical Microfluidics

Main requirements to the flow sensors of biomedical designation are the following: biomedical compatibility of the materials and the ability to measure small values of the velocity (mass transfer) of the studied fluid or gas flow.

If these sensors are used for studying the parameters of the respiration system the main requirement is minimal inertia and ergonomic indices. Sensors for biomedical in-situ studies must be characterized by minimal dimensions and energy consumption.

3. CONSTRUCTION AND FUNCTIONAL CHARACTERISTICS OF MICROELECTRONIC FLOW SENSORS OF BIOMEDICAL AND ECOLOGICAL DESIGNATION

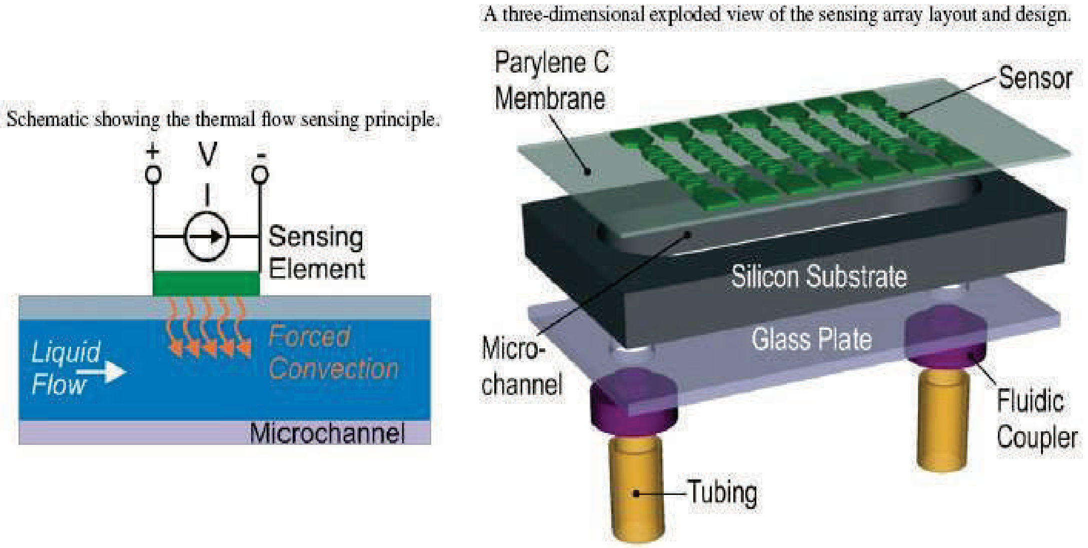
In particular, Figure 15 shows the construction and functional characteristics of microelectronic flow sensors of biomedical designation [9]. The sensor is manufactured in the base of LTCC (Low Temperature Coffered Ceramics) using the elements of thick-film technology, that provides biomedical compatibility with the investigated fluids.



a) b)

Figure 15 – LTCC – based microelectronic flow sensor of biomedical designation:
a) construction; b) functional characteristics

Another typical example of the flow sensor of biomedical designation is the microelectronic module of the base of biocompatible MEMS matrix [7]. Matrix of the sensor is realized on the base of biocompatible Parylene C Membrane with platinum sensor electrodes. In order to improve the heat insulation of the thermal flow sensor its membrane is "suspended" above the beamed micromechanical channel made of silicon. Principle of the functioning and the design of the sensor are shown in Figure 16, succession of its structure formation – in Figure 17, exterior view – in Figure 18. Wide range of functional characteristics of the given flow sensor in various operation modes can be seen in Figures 19 – 22.



a) b)

Figure 16 – Microelectronic flow sensor of biomedical designation on the base of Parylene C membrane [7]: a) functional principle; b) design

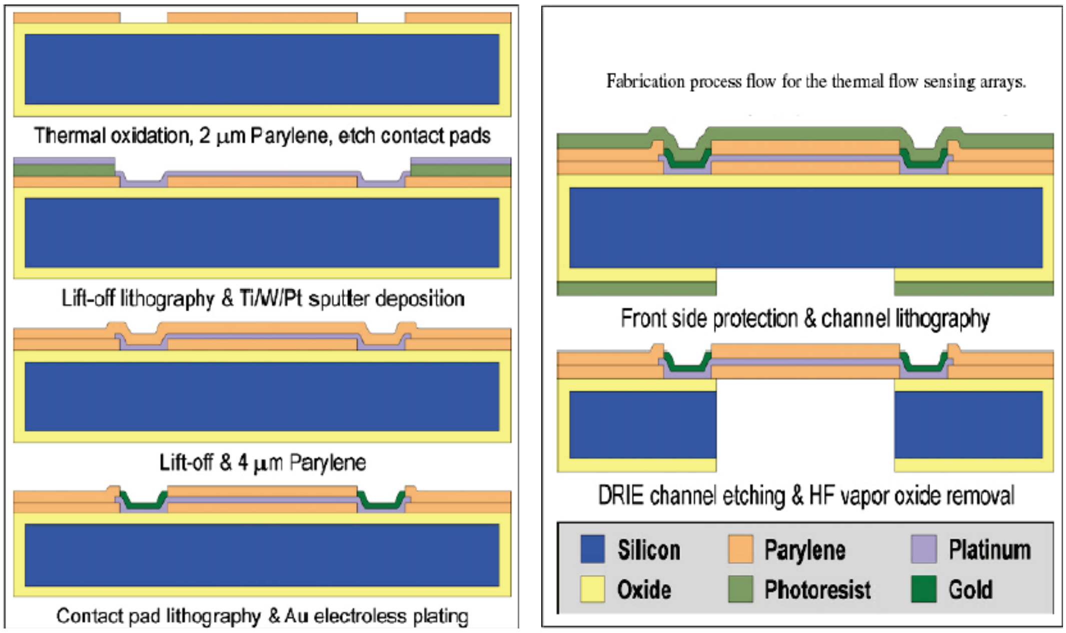


Figure 17 – Succession of flow sensor structure formation [46]

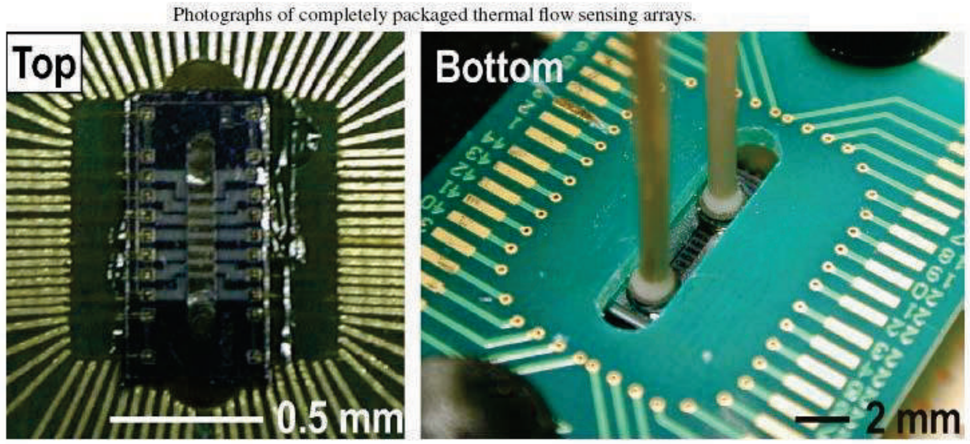
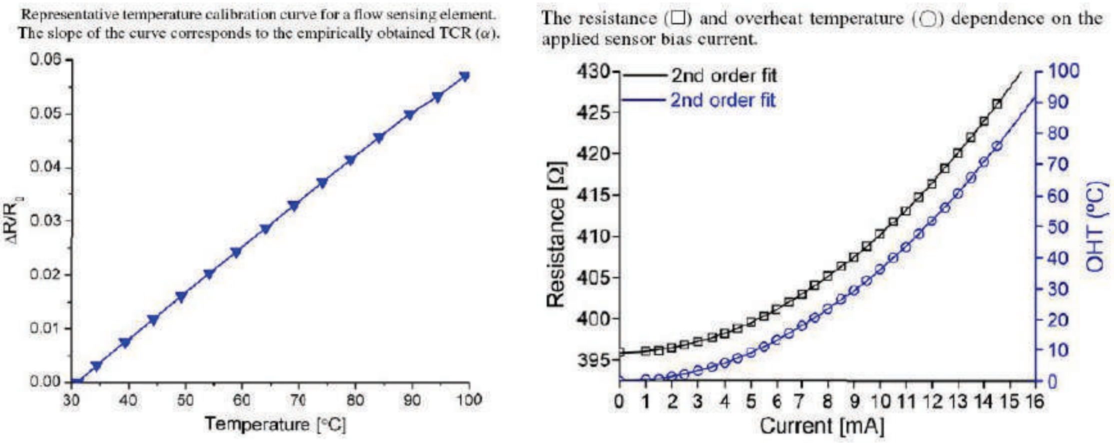
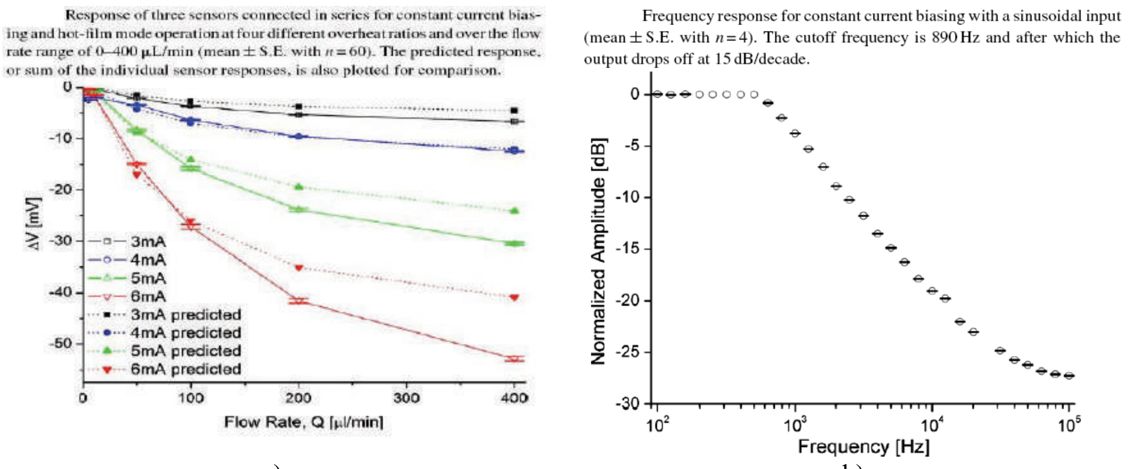


Figure 18 – Exterior view of the flow sensor [7]



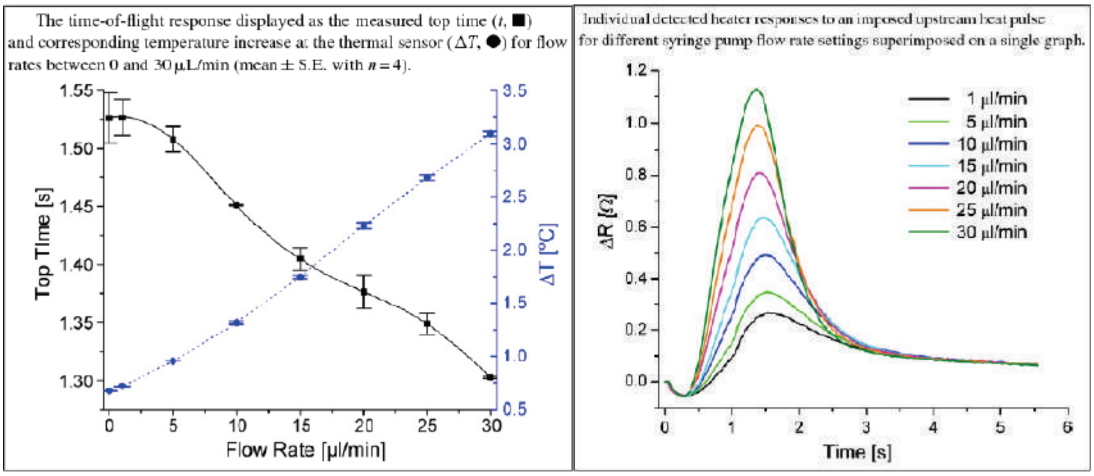
a) b)

Figure 19 – Characteristics of the thermoresistive elements of the flow sensor [7]:
a) temperature; b) current



a) b)

Figure 20 – Characteristics of the thermoresistive elements of the flow sensor [7]:
a) functional; b) frequency


The time-of-flight response displayed as the measured top time (t, ■) and corresponding temperature increase at the thermal sensor (ΔT, ●) for flow rates between 0 and 30 μL/min (mean ± S.E. with $n = 4$).

Individual detected heater responses to an imposed upstream heat pulse for different syringe pump flow rate settings superimposed on a single graph.

Figure 21 – Temporal functional characteristics of the flow sensor [7]

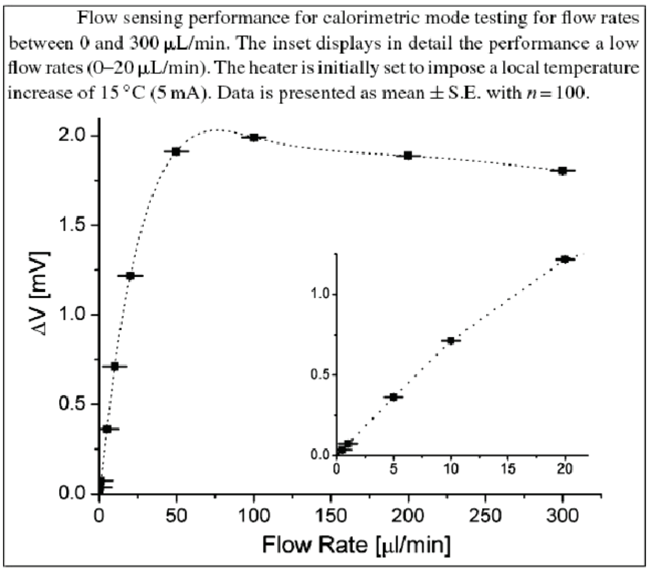

Flow sensing performance for calorimetric mode testing for flow rates between 0 and 300 μL/min. The inset displays in detail the performance a low flow rates (0–20 μL/min). The heater is initially set to impose a local temperature increase of 15 °C (5 mA). Data is presented as mean ± S.E. with $n = 100$.

Figure 22 – Functional flow sensor performance for high and low flow rates [7]

CONCLUSIONS

Analysis of the characteristics of the considered sensors enables us to make a number of important conclusions.

- First, modern microelectronic flow sensors, in particular, sensors of biomedical designation, are characterized by a great variety of signal formation principles – from the elementary linear converters, based on one sensitive element to non-linear (generation, time-dependent) converters, based on the matrices of the functionally integrated elements. Realization of these principles puts forward the problem of the development of the corresponding signal converters that meet the requirements of modern microelectronics.
- Secondly, the expansion of the range of flow rates measurement causes certain problems – the characteristics of the sensor's conversion which enable it to measure small flows becomes non-linear at the increase of the flow rate. At certain critical values of the velocity the extremum of the transformation function is observed, it makes impossible the measurement of both small and great velocities. The solution of this problem requires the corresponding control over the thermal power of the sensor heaters and a number of other circuit engineering solutions. Thirdly, the problem of energy supply of thermal flow sensors remains actual. It is especially typical for the supply of the sensors of biomedical designation from autonomous, small-size low power, low voltage electric chemical elements The heating of the flow substances as compared with the energy supply of modern micro power CMUS of the integrated circuits requires greater energy. Besides, with the decrease of the

supply voltage (for the small-size, self-contained supply sources it is typically not more than *3V*), it is necessary to decrease the resistance of the heating elements. Applying functionally integrated elements used both for heating and the measurement of the temperature, the decrease of the resistance (as a rule, to the values of less than 100 ohm) leads to parasitic impact on the result of signal lines measurement. Thus, the decrease of energy consumption (power and heating temperature) leads to the advent of the parasitic impact of signal lines resistances and, as a result, to worsening of the functional characteristics, in particular, decrease of the accuracy of flow rate measurement.

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PAVLOV SERGII – D.Sc., Professor of Biomedical Engineering and Optic-Electronic Systems Department, Vinnytsia National Technical University, ***e-mail: psv@vntu.edu.ua***

WÓJCIK WALDEMAR – D.Sc., Professor, director of the Institute of Electronics and Information Technology at Lublin University of Technology. Doctor Honoris Causa of five universities in Ukraine and Kazakhstan, ***e-mail: waldemar.wojcik@pollub.pl***

HOLYAKA ROMAN – D.Sc., Professor of Electronic Device of Information-Computer Technologies Department, Lviv Polytechnic National University, ***e-mail: roman.I.holiaka@lpnu.ua***

AZAROV OLEXIY – D.Sc. Professor, head of Computer Technology Department, Vinnytsia National Technical University, ***e-mail: azarov.olexiy@gmail.com***

BOHOMOLOV SERGIY – Ph.D., Docent of Computer Technology Department, Vinnytsia National Technical University, ***e-mail:bogomolovsergiyt@vntu.edu.ua***

YANG LONGYIN – M.Sc., post-graduated student of Biomedical Engineering and Optic-Electronic Systems Department, Vinnytsia National Technical University, ***e-mail: longyinyang966@gmail.com***