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Thermal radiator sensor

Khudoyor Urinov[1], *Khakberdi* Jumanov[1], *Khotam* Mirzokulov[1], *Abduvali* Xidirov[1],
Adham Amonov[2], *Mirzo* Sharipov[3*], and *Jamshid* Urinov[1]

[1]Samarkand branch of Tashkent University of Information Technology named after Mukhammad al-Khwarizmi, Samarkand, Uzbekistan
[2]Samarkand branch of Tashkent State University of Economics, Samarkand, Uzbekistan
[3]Bukhara Engineering Technological Institute, Bukhara, Uzbekistan

Abstract. This study addresses the challenges of simplifying the design for measuring the thermomagnetic properties of thin magnetic films and developing a novel thermal radiation sensor. The proposed sensor features a vanadium dioxide (VO2) film element that converts heat flow into a thermoelectric current. A reflective screen, electrically isolated from the film, covers part of its surface. The film includes electrical contacts with current leads. This innovative design enables the measurement of thermomagnetic properties and offers a new approach for thermal radiation sensing.

1 Introduction

There is a large set of measuring instruments that allow measurements of heat and radiation fluxes. There is a wide class of thermal radiation sensors bolometers [1-4]. The basis of their work is the change in the resistance of a sensitive element, metal or semiconductor, from temperature. The change in temperature of the sensor is caused by the absorption of thermal energy. Thus, by measuring the resistance of the sensitive element, it is possible to fix the power of thermal radiation.

A thermal radiation sensor, also known as an infrared (IR) sensor or radiometer, is a device that detects and measures the thermal radiation emitted by objects. Thermal radiation is a form of electromagnetic radiation emitted by an object due to its temperature. Infrared sensors are commonly used for various applications, including temperature measurement, thermal imaging, and industrial process control.

Thermal radiation sensors typically work based on the principle of absorbing and detecting the infrared radiation emitted by an object. The sensor consists of a thermoelement or a thermopile that generates a voltage proportional to the temperature difference between the object being measured and the sensor itself. This voltage can then be converted into a temperature reading.

Thermal radiation sensing, a cornerstone of modern sensing technology, plays a pivotal role in a diverse array of fields, revolutionizing industrial processes, advancing medical imaging, and contributing crucial insights to climate science. This fundamental sensing technique capitalizes on the intrinsic relationship between an object's temperature and the

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* Corresponding author: m.z.sharipov@rambler.ru

radiation it emits, offering a non-contact and reliable means to measure, monitor, and interpret thermal phenomena.

In the realm of industrial processes, thermal radiation sensing emerges as an indispensable tool for optimizing efficiency, ensuring product quality, and maintaining safety. From steel manufacturing to semiconductor fabrication, monitoring the temperatures of furnaces, reactors, and critical components is imperative. Thermal radiation sensors enable real-time temperature measurements in environments where direct contact is unfeasible due to extreme conditions or contamination risks. By providing accurate thermal data, these sensors facilitate timely adjustments, prevent overheating, and enhance overall process control, translating into increased productivity and reduced downtime.

The medical field has witnessed transformative advancements through the integration of thermal radiation sensing. In medical imaging, techniques like thermography harness the inherent temperature variations of the human body to diagnose a range of conditions. Breast cancer detection, for instance, benefits from thermal imaging's ability to visualize abnormal heat patterns indicative of malignancies. Furthermore, non-invasive temperature monitoring during surgical procedures and wound healing becomes attainable, minimizing patient discomfort and accelerating recovery. Thermal radiation sensors empower medical professionals with invaluable insights into physiological processes that were previously inaccessible without invasive procedures.

Understanding Earth's complex climate dynamics necessitates precise measurements of radiative energy exchanges between the planet's surface and the atmosphere. Thermal radiation sensing has proven indispensable in quantifying these energy transfers, providing pivotal data for climate models. Instruments aboard satellites and ground-based observatories capture the Earth's emitted thermal radiation, allowing scientists to analyze temperature trends, map heat distribution, and study phenomena like urban heat islands and sea surface temperatures. This data is pivotal for gauging the impacts of climate change, guiding policy decisions, and formulating mitigation strategies.

In the interconnected landscape of technology, health, and the environment, thermal radiation sensing emerges as a versatile and indispensable tool. Its applications span from enhancing industrial operations and optimizing medical diagnoses to unraveling the intricacies of our planet's climate system. The non-intrusive nature of thermal radiation sensing, coupled with its accuracy and versatility, has propelled it to the forefront of modern sensing technologies, influencing advancements across diverse fields and shaping the trajectory of innovation. As we delve deeper into the multifaceted potentials of this technique, its role is poised to expand further, driving novel discoveries and transforming industries in ways previously unimagined.

Certainly, let's provide an overview of the main types of thermal radiation sensors.

Thermopiles [5] are temperature sensors that utilize the Seebeck effect to measure temperature differences. A thermopile consists of multiple thermocouples connected in series or parallel. Each thermocouple generates a small voltage proportional to the temperature difference between its two junctions. By combining the outputs of multiple thermocouples, thermopiles can detect even subtle temperature changes. They are commonly used in applications requiring contactless temperature measurements, such as industrial process control and automotive applications.

Bolometers [6] are highly sensitive detectors of infrared radiation. These sensors operate on the principle that when incident radiation is absorbed by a material, its temperature increases, causing a change in its electrical resistance. This change in resistance can be measured to infer the intensity of the incident radiation. Bolometers are used in various fields, including astronomy, thermal imaging cameras, and scientific research, where precise measurements of weak infrared signals are essential.

Pyroelectric sensors [7] are capable of detecting changes in temperature by exploiting the pyroelectric effect, where certain materials generate a voltage in response to temperature variations. Pyroelectric materials possess a built-in electric charge, and when exposed to temperature fluctuations, they generate a voltage proportional to the rate of change of temperature. Pyroelectric sensors find applications in motion detection (such as in security systems), gas analysis, and non-contact temperature measurements.

Microbolometers [8] are advanced thermal detectors used in thermal imaging systems. They are composed of tiny pixel-sized structures that change their electrical resistance when exposed to varying levels of infrared radiation. The change in resistance is measured and converted into an image, forming a thermal map of the scene. Microbolometers are pivotal in applications like night vision, surveillance, and medical imaging due to their ability to detect subtle temperature differences and produce real-time thermal images.

Each of these thermal radiation sensors has its unique strengths and applications. They are employed across various industries and fields, including industrial automation, aerospace, medical diagnostics, climate research, and consumer electronics, contributing to advancements in temperature sensing, thermal imaging, and radiation detection.

There are other types of thermal radiation sensors, these are sensors containing an element with a surface that absorbs radiation, a thermocouple battery and current outputs [9]. The operation of such a sensor is based on the occurrence of a thermoelectromotive force (thermoEMF) when heating thermocouple junctions due to absorption of thermal radiation. The use of pure substances Bi, Sb, ... and complex semiconductor compounds as thermocouples, such as, and placement on a screen area of 1mm^2 up to hundreds of thermal junctions allows thermal sensitivity to be recorded with high sensitivity and radiation fluxes. The given sensor options have a number of disadvantages. So, bolometers, for example, need electric power and a special coating to effectively absorb heat flux. And the lack of a sensor with a thermocouple battery is the design complexity and low reliability. The given sensor options have a number of disadvantages. So, bolometers, for example, need electric power and a special coating to effectively absorb heat flux. And the lack of a sensor with a thermocouple battery is the design complexity and low reliability.

A thermoelement, also known as a thermocouple, is a temperature sensor that relies on the Seebeck effect, which is the phenomenon of a voltage difference being created between two different conductors when there is a temperature gradient between them. This voltage difference can be used to measure the temperature.

A thermoelement consists of two different types of metals or semiconductors joined together at two points. These points are exposed to different temperatures—one being the measurement point (where the temperature needs to be measured) and the other being the reference point (usually at a known temperature).

As the temperature at the measurement point changes, a voltage is generated across the two junctions of the thermoelement. This voltage is directly proportional to the temperature difference and can be measured using appropriate instrumentation. By calibrating the thermoelement and knowing the properties of the materials used, you can accurately determine the temperature at the measurement point.

Vanadium dioxide V02 has a remarkable property, the metal-insulator phase transition (MIPT). The phase transition is accompanied by a sharp change in electrical, magnetic, optical and other characteristics.

Vanadium dioxide (VO2) is a unique material that has gained attention for its remarkable properties, particularly its metal-insulator transition near room temperature. This transition has significant implications for enhancing the performance of thermal radiation sensors and related devices. Here's how VO2 contributes to sensor performance:

- Temperature Sensitivity.VO2's metal-insulator transition occurs around 68°C (154°F), which is close to typical room temperatures. This property makes VO2 an excellent candidate for temperature-sensitive applications. When used as a sensing material in thermal radiation sensors, VO2 can enable precise temperature measurements and imaging without the need for external temperature stabilization.

- Tunable Emissivity. VO2's transition from insulating to conducting behavior affects its optical properties, including its emissivity. Emissivity is a crucial factor in thermal radiation sensing, as it determines how efficiently an object emits and absorbs radiation. By exploiting VO2's tunable emissivity properties near its transition temperature, sensors can be designed to respond selectively to certain wavelengths, improving their accuracy and sensitivity.
- Energy-Efficient Devices. VO2's transition is accompanied by significant changes in its electrical conductivity and optical properties. This property has the potential to create energy-efficient devices. For example, VO2-based smart windows can modulate the transmission of heat and light based on temperature changes, reducing the need for active heating and cooling systems and contributing to energy savings.
- Fast Response Time. The transition of VO2 from insulator to conductor occurs rapidly—within fractions of a second. This fast response time can be exploited in sensors to achieve real-time measurements and rapid imaging in applications where quick changes in temperature need to be detected and monitored.
- Miniaturization and Integration. VO2 can be fabricated into thin films and integrated into microdevices, making it suitable for miniaturized and portable thermal radiation sensors. The material's unique properties can be harnessed to develop compact and highly functional sensors for various applications, such as wearable devices and IoT-enabled systems.
- Multi-Functional Devices. VO2's properties extend beyond thermal radiation sensing. Its transition can be influenced by external factors like electrical fields, strain, and pressure. This multifunctionality enables the creation of sensors that respond not only to temperature but also to other stimuli, broadening their application possibilities.

Incorporating VO2 into thermal radiation sensors holds the potential to revolutionize the field, enabling devices with enhanced sensitivity, fast response times, and the ability to operate under varying temperature conditions. Researchers continue to explore and optimize VO2-based sensors, pushing the boundaries of sensor technology and unlocking new capabilities for a wide range of applications.

Using VO2 in thermoelectric devices has both benefits and challenges:

Benefits:

Near Room Temperature Operation: VO2's phase transition occurs close to room temperature, making it suitable for applications where temperature differentials are moderate.

High Thermoelectric Performance: The transition in electrical conductivity can lead to substantial changes in thermoelectric properties, potentially enhancing the device's efficiency.

Compact Devices: The small temperature difference required for the MIT makes it feasible to create compact and efficient thermoelectric modules.

Challenges:

Material Properties: While VO2 has potential, its thermoelectric properties still need further optimization to achieve higher efficiency and performance.

Thermal Management: As with any thermoelectric device, managing temperature differentials and heat dissipation is crucial for efficiency and reliability.

Manufacturing Complexity: Fabricating and integrating VO2-based thermoelectric devices can be challenging due to the specific material characteristics and the need for precise control during the manufacturing process.

To date, for all members of the series, except for, a phase transition has been found in which the properties of oxides change stepwise. Since the resistance value upon reaching the PT temperature T_k changes in times [10], this property is used in this device. Devices that use the material of the system already exist and their number is constantly growing [11]. The scientific literature focuses on the study of the metal-insulator phase transition in thin layers of vanadium dioxide V02. Which, apparently, is caused in the first place because thin films are more technologically advanced in production, secondly, this is due to the temperature of the phase transition (340 K) and the possibility of widespread use of V02 in various fields of technology [12-17].

2 Materials and methods

Thermal radiation is the process by which all objects with a temperature above absolute zero emit electromagnetic radiation due to their thermal energy. This radiation is in the form of photons, and its intensity and wavelength distribution are directly related to the object's temperature.

According to the principles of thermodynamics, temperature is a measure of the average kinetic energy of the particles within an object. As an object's temperature increases, the kinetic energy of its particles also increases. These energetic particles move and vibrate more vigorously, which leads to the emission of photons at higher frequencies and shorter wavelengths.

The relationship between thermal radiation and temperature is described by several key principles:

Stefan-Boltzmann law states that the total energy radiated by a blackbody (an idealized object that absorbs and emits all radiation) is proportional to the fourth power of its absolute temperature (measured in Kelvin). Mathematically, it's expressed as:

$$E = \sigma * T^4 \tag{1}$$

where E is the total energy radiated, σ is the Stefan-Boltzmann constant, and T is the absolute temperature.

Wien's Displacement Law establishes the relationship between the temperature of a blackbody and the wavelength at which it emits the most radiation. It states that the peak wavelength (λ_{max}) of the emitted radiation is inversely proportional to the absolute temperature (T) of the object

$$\lambda_{\max} * T = cons\ . \tag{2}$$

As temperature increases, the peak of the radiation spectrum shifts to shorter wavelengths, meaning the object emits more energy in higher-energy (shorter) photons.

In simpler terms, as an object's temperature rises, it emits more thermal radiation, and the radiation it emits becomes more energetic. This principle is the basis for many applications, including thermal imaging, temperature measurement, and energy transfer in various processes.

Emissivity (ε) is a material property that characterizes how efficiently an object emits thermal radiation relative to an ideal blackbody. An object with an emissivity of 1 is a perfect blackbody emitter, while an object with an emissivity less than 1 emits less radiation. Emissivity takes into account the reflective and absorptive properties of a surface. Dull, dark surfaces tend to have higher emissivities compared to shiny, reflective surfaces.

Emissivity affects both the intensity and spectral distribution of an object's emitted radiation. Real-world objects with varying emissivities emit radiation differently based on their material properties and surface conditions. In thermal radiation sensors, understanding the emissivity of the object being measured is essential for accurate temperature calculations.

In summary, the principles of thermal radiation are rooted in the temperature-dependent emission of electromagnetic radiation by objects with thermal energy. The Stefan-Boltzmann Law quantifies the total energy emitted, while Wien's Displacement Law describes the relationship between temperature and peak emission wavelength. Emissivity adds another layer of complexity by influencing how efficiently an object emits radiation, making it a critical factor in practical temperature measurements and applications.

The sensor, thermocouple [12,13], works as follows. The flow of thermal energy is absorbed by the uncoated part of the vanadium dioxide film and heats it. The part of the V02 film covered by the screen has a lower temperature, because in this case the absorption of thermal energy does not occur. The change in temperature of this part of the vanadium dioxide film is caused only by the process of heat conduction from its more heated uncovered part of the film through its cross section. If the temperature of the open part of V02 reaches the temperature of the MIPT [18-20], 340 K, a metal-insulator phase boundary arises, and the corresponding potential difference, which is due to the different work function of the electrons from the dielectric and metal phases. Since the film is made of a homogeneous material [21-23], the value of the contact potential difference does not depend on the position of the metal-insulator phase boundary on the surface of the vanadium dioxide film. But since the phase conductivities differ significantly, the thermal current through the film cross section depends on the position of the metal-insulator interface.

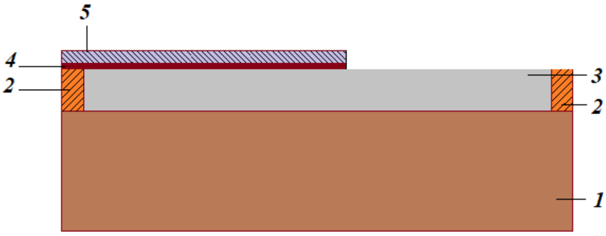

Fig. 1. General view of the thermal radiation sensor (thermoelement) 1-isolating substrate, 2- contacts with current leads, 3- film of vanadium dioxide, 4- dielectric layer, 5- reflective screen.

If the heat flux power changes, due to the thermal conductivity of the film, the phase boundary changes its position, while the thermal current is a monotonic function of the heat flux power, general view of the thermal radiation sensor demonstrated in Fig. 1.

The propagation of the heat flux through the cross section of the V02 film, vanadium dioxide, from the unclosed to the closed part obeys the Fourier law:

$$q = -\lambda \frac{dt}{dx} \tag{3}$$

with boundary conditions $T(a) = T_0$.

The solution to equation (3) has the following form

$$T = T_0 + \frac{q}{\lambda}(a - x) . \tag{4}$$

The position of the metal-insulator phase boundary is determined from the equation:

$$T_k = T_0 + \frac{q}{\lambda}(a - x) \tag{5}$$

where Tk is a temperature of the MIPT, a is a value determining the total longitudinal length of the vanadium dioxide film, x is the dielectric part of vanadium dioxide film at the temperature of the the MIPT.

Assuming that the resistance of the dielectric phase is much greater than that of the metal phase 3-4 orders of magnitude in experiment [6], we obtain for the internal resistance of the thermocouple:

$$R=\frac{a-x}{S}\cdot\rho;\quad R=\frac{T_k-T_0}{qS}\cdot\lambda S\ . \tag{6}$$

Thermal current is determined by the ratio of the contact of the potential difference and the internal resistance:

$$J=\frac{\Delta\varphi qS}{(T_k-T_0)\lambda q} \tag{7}$$

where T0-thermostat temperature; λ-coefficient of thermal conductivity; ρ- resistivity; S-sectional area; q-density heat flux; Δφ is the contact potential difference.

Sign the analytical relationship between the characteristics of the sensor and with known parameters, you can evaluate the contact potential difference from equation (8):

$$\Delta\varphi=\frac{J(T_k-T_0)}{qS}\cdot\lambda\rho;\quad \Delta\varphi=0{,}8\cdot10^{-8}W\ . \tag{8}$$

Table 1. Value of parameters for calculating.

Parameters	Value	Unit
λ	6.07	W/cm·K
T_k	340	K
T_0	293	K
l	0.5	cm
J	2.75	μA
$\rho(VO_2)$	50	Ω-cm
d	4.7	cm
q	2	W/cm

Now calculating Δφ according to Ohm's law, consider the vanadium dioxide film as a chain segment:

$$\Delta\varphi=JR,\quad R=\rho\frac{l}{S},\quad \Delta\varphi=0{,}4\cdot10^{-8}W\ . \tag{9}$$

3 Results and discussion

The experiment was carried out as follows: a thermal energy flow was directed to the temperature sensor, due to which the unshielded part of the sensitive element of vanadium dioxide was heated. After the element is heated to the MIPT temperature, the thermal current is measured at the current output contacts.

Comparing these results of the calculation of the contact potential difference, it is clear that the numbers of the same order are obtained. Therefore, we can conclude that the analytical relationship of the sensor parameters with the measured values is done correctly.

The dynamic range of the thermal radiation sensor is determined by the size of the vanadium dioxide film and the ratio of the closed and open parts of the screen. So the minimum value of the measured power flux is determined by the absorption coefficient, and, as can be seen from Fig. 2, is approximately 1 W/cm^2.

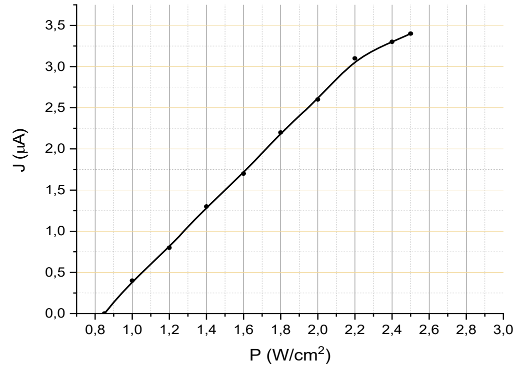

Fig. 2. The minimum value of the measured power flux determined by the absorption coefficient.

The maximum power flow is determined by the length of the film and may be limited by the melting of the uncovered portion of the thermocouple screen.

In contrast to the V02 single crystal which is destroyed after several MIPT thermal cycles, thin layers can withstand significantly / up to several thousand/ thermal cycles, which is explained by adhesion with a dielectric substrate.

So, the proposed thermal radiation sensor has significant features, Firstly, in that, unlike traditional thermocouples, the junction temperature here is always the same and is 340 K. Secondly, in this case we always deal with a physically clean contact.

4 Conclusion

The proposed sensor in its technical essence has some similar features of traditional thermal radiation detectors of thermocouple batteries and bolometers. On the one hand, the heat flux causes thermo-EMF, on the other hand, a change in the internal resistance of the sensitive element. However, a combination of these two effects in one material has not been implemented.

A thermal radiation sensor containing an absorbing surface and an element that converts heat flux into thermoelectromotive force made of a film of vanadium dioxide V02 with contacts, part of the surface of which is closed in a reflective screen.

Thus, studies of MIPT in V02 films of various thicknesses on various substrates. It was shown that a decrease in the transition temperature in the films is due to surface phenomena at the film-substrate interface.

Based on the MIPT in V02 films, a thermal radiation sensor has been developed and manufactured.

Thermal radiation sensors find diverse applications in fields that require non-contact temperature measurement, thermal imaging, and infrared spectroscopy. Here are some of the prominent application areas.

Thermal radiation sensors are extensively used for accurate and non-contact temperature measurement in various industries, including:

In industrial Processes for Monitoring temperatures in manufacturing processes such as metal casting, glass production, and semiconductor fabrication to ensure product quality, optimize energy consumption, and prevent overheating.

HVAC (Heating, Ventilation, and Air Conditioning): Ensuring proper temperature control and energy efficiency in buildings by measuring the temperature of HVAC components and spaces.

Monitoring temperatures during food production and storage to maintain hygiene and prevent spoilage.

Thermal imaging cameras equipped with thermal radiation sensors capture the infrared radiation emitted by objects, producing images that represent temperature variations across a scene. Applications include:

Detecting insulation gaps, water leaks, and electrical faults in structures to enhance energy efficiency and safety.

Identifying intruders, anomalies, and thermal patterns in dark or obscured environments for security purposes.

Visualizing temperature differences in the body for diagnosing conditions, such as identifying inflammation, injuries, or circulation issues.

Infrared spectroscopy involves analyzing the interaction of materials with infrared radiation. Thermal radiation sensors play a role in this field in applications like:

Identifying chemical compositions and material properties by analyzing the unique infrared absorption and emission spectra of substances.

Studying atmospheric composition and pollution levels by detecting specific infrared absorption bands of gases and particles.

Characterizing molecular structures and interactions in drug development and quality control using infrared spectroscopy.

The versatility of thermal radiation sensors makes them invaluable tools across industries, providing insights into temperature variations, material properties, and heat-related phenomena. As technology advances, these sensors continue to impact a wide range of applications, contributing to innovation, safety, and sustainability.

The integration of thermal radiation sensing with other cutting-edge technologies, such as Artificial Intelligence (AI) and the Internet of Things (IoT), holds immense potential to revolutionize various industries and applications. This convergence can lead to smarter, more efficient systems with enhanced capabilities.

In this comprehensive review article, we explored the principles, technologies, and applications of thermal radiation sensors—a cornerstone of modern sensing technology. We delved into the fundamental concepts of thermal radiation, including the Stefan-Boltzmann Law and Wien's Displacement Law, which underpin the relationship between temperature and emitted radiation.

We highlighted the main types of thermal radiation sensors, such as thermopiles, bolometers, pyroelectric sensors, and microbolometers, each with distinct mechanisms for detecting and measuring thermal radiation. These sensors find applications across diverse fields, including temperature measurement, thermal imaging, and infrared spectroscopy.

The role of specific materials, particularly vanadium dioxide (VO2), was explored. VO2's unique metal-insulator transition near room temperature offers enhanced temperature sensitivity, tunable emissivity, and fast response times, which contribute to improving sensor performance and enabling energy-efficient devices.

The article underscored the wide range of applications for thermal radiation sensors. From monitoring industrial processes, enhancing medical imaging, and advancing climate research to enabling IoT-connected systems and automating decision-making through AI, thermal radiation sensors play a pivotal role in modern technology.

The integration of thermal radiation sensing with AI and IoT was discussed as a pathway to smarter and more efficient systems. AI-driven analysis of thermal data and IoT-enabled remote monitoring present opportunities for real-time insights, automated responses, and optimized resource management.

In conclusion, thermal radiation sensors are indispensable tools across industries and research fields. Their ability to provide non-contact temperature measurements, thermal imaging, and infrared spectroscopy data influences decision-making, improves efficiency, and enhances safety. As technology advances and interdisciplinary collaborations continue, the importance of thermal radiation sensors in shaping the future of technology and research cannot be overstated.

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