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Generalization of the thermal model of infrared radiation sensors

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ABSTRACT

In many theories and applications, generalized models can give a good head start for further research where the implementation of new elements and/or boundary conditions could become quite complex. In this paper the development of a compact thermal model of an infrared sensor will be presented. This thermal model includes not only the thermal resistances and capacitances of the sensor structure itself but the radiative and convective thermal resistances to the ambience and between the sensor plate and the heat source (thermal transfer impedance) which is important when the heat source and the sensor are in close proximity. Limitations and the applicability of the proposed model are also discussed. We also aim to present how the proposed model can be used for other IR sensor structures as well.

1. Introduction

The infrared sensor card (Fig. 1) presented in paper [1] enables temperature mapping of different circuits and assembled boards. With the presented method the infrared (IR) radiation-distribution of boards from the close proximity of the sensor card can be monitored, enabling in situ IR measurement between operating cards of a system e.g. in a rack, ATX or BTX type systems. Using this contactless temperature mapping method the temperature distribution and the locations of hot-spots in an operating assembled printed circuit board can be identified in a dense rack system, where only a thin measurement board could be inserted between the operating cards. Determining the exact place of the hot-spots the reliability of an electronic system can be improved.

In the previous work presented in paper [2] our main goals were to reduce the thermal time constant of the sensor card and to minimize the thermal crosstalk effect between the adjacent sensor pixels. The thermal time constant was successfully reduced by decreasing the thermal capacitance of a sensor pixel. Lowering the thermal time constant allows better time resolution of real time transient detection of hot spots. Reduced thermal crosstalk allows more accurate spatial detection of hot-spots.

Although a detailed lumped element model was presented in [2] and can be seen in Fig. 2, the analytically calculated time constant differed from the results of the measurements of a real situation. The difference was more than 40%. This error was caused by the total negligence of the radiative thermal transfer impedance between the heat source and the sensor. The stimuli in case of the simulations and of the initial measurements were a power step which was applied on the diode of the adequate pixel. This method supposes the total absorbance of the radiated thermal radiation of a distant source. This way only the thermal time constant of the pixel itself can be determined but not the exact time constant of the entire measurement setup.

Additionally, measurements in electrical system are typically carried out in close proximity arrangement. In our case close proximity means that the side length of the pixel can be compared to the distance of the sensor and the heat source. In this case the parasitic effects (e.g.: conductance of the filling gas, convective and radiative heat transfer between the sensor pixel and the measured unit) should be taken into account in the model. In [2] the thermal radiation was considered only when the crosstalk effect between pixels was determined and it was neglected in the model and when the time constant was calculated.

In this paper a new thermal compact model is presented which consists of the radiative thermal transfer impedance between the heat source and the sensor. Limitations and the applicability of this model are also discussed. Since the radiative thermal transfer impedance depends on the temperature of the heat source and the distance between the heat source and the sensor pixel so this model is applicable to determine the thermal behaviour and the time constant of the whole measurement arrangement. The analytical calculation of the time constant was verified by simulations and measurements. The results and comparison to the analytical calculation are also presented.

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2. Sensors for contactless thermal measurement

The thermal emission described by the Planck relationship is a function of the temperature of the bodies and the emissivity. The intensity of the radiation and the peak wavelength (λ_{max}) decrease with the temperature (T) as it is described byWien's displacement law:

$$\lambda_{max} \cdot T = 2897.8\ [\mu m\ \mathrm{K}] \qquad (1)$$

The temperature of the terrestrial objects are typically about 300 K which results in a peak emission in far infrared (FIR) with wavelengths near 10 μm.

The two principal types of far infrared (FIR) detectors are photon detectors and thermal detectors [3,4]. In photon detectors the absorbed photons directly produce free electrons or holes. In thermal detectors the absorbed photons produce a temperature change, which is indirectly detected by measuring the temperature-dependent property of the detector material.

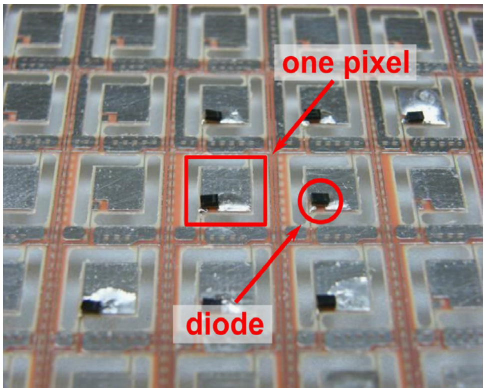

Fig. 1. The sensor card with minimal area diodes before black painting [2].

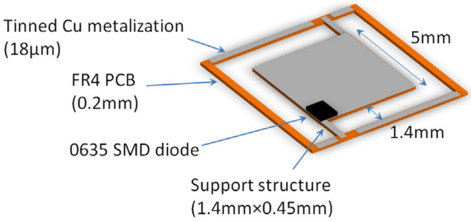

Fig. 2. The structure of a pixel.

Photon detection-based infrared imaging arrays are typically made of II–VI or III–V direct band-gap semiconductors based sensors. These sensors are very expensive thanks to the difficult processing and manufacturing technologies and require cooling and cryogenic temperatures. Photon detectors have either a small forbidden energy gap (narrow bang-gap) or small donor/acceptor activation energy. Its operation requires that most of the free carriers in the photon detector be excited by the radiating bodies and not by the thermal excitation associated with the operating temperatures of the detector itself [5,6]. In the case of HgCdTe based sensors the narrow band-gap—thus the spectral sensitivity—can be tuned by the composition of compound, so a wide range (2–15 μm of wavelength) can be achieved [7].

The uncooled MEMS (micro-electro-mechanical system) based thermal detector arrays provide lower-cost, compact thermal imagers. There are several types of uncooled infrared sensors. All of these sensors are heated up by the incoming infrared radiation and the temperature change can be measured by one of the following methods: resistance change (bolometer) or thermoelectric junction or pyroelectric effect or liquid crystal colour change, etc. [3].

Uncooled far infrared detectors realized by MEMS technology are mostly based on microbolometer or thermopile technology [8]. Thanks to the MEMS technology small sensor array can be realized also on a silicon die similar to CCD or CMOS sensors. The sensing method is the only difference between them. The main advantage of these types of sensors is their relatively small time constant (~10 ms). [3] The thermal time constant of these microstructures is in the range of 100 us–1 ms which is based on the small heat capacitance of the sensor itself and the high thermal resistance between the sensor and the silicon substrate. This way the incident low energy can heat up the MEMS sensor within a relatively short time.

However a common disadvantage of these types of sensors is that different optical elements and lenses are required by the applications and measurements to get a relatively wide viewing angle. In order to direct and focus down the incident thermal radiation onto the infrared sensor (e.g. focal plane array) expensive and large lenses are required. Usually these lenses are made of germanium or silicon to keep out the optical radiation. With these additional elements the whole thermal sensor system may not be placed between two cards in e.g. a rack system. That is why the heat distribution cannot be visualized in this way. An additional problem is that cooled type IR cameras need liquid gases during the operation [9].

Essentially based on these thermal imaging techniques a new type of far infrared sensor was developed without the requirement

Table 1
Comparison of different type of FIR sensors.

	Photon detector [9,6]	Resistive bolometer [3,11,10]	Pyroelectric sensor [3,12]	Thermoelectric sensor [13–15]	Sensor presented in this paper
Physics	Changing number of free carriers	Carrier density change	Dielectric polarization	Seebeck effect	Changing of diode forward voltage
Signal	Current change—dI	Resist. change—dR	Polarization—dQ	Voltage change—dV	Voltage change—dV
Cooling required	Yes	No	No	No	No
Responsivity	High	High	High	High	Low
Bias required	Yes	Yes	No	No	Yes
DC response	Yes	Yes	No	Yes	Yes
Response time	Very small (us range)	C/G—Small (100 us range)	C/G—Small (100 us range)	C/G—relatively small (ms range)	high (10 s range)
Price	Very expensive	Relatively expensive	Relatively expensive	Relatively expensive	Very cheap
Ge lens required	Yes	Yes	Yes	Yes	No
Main purposes	Thermal imaging	Thermal imaging night vision	Thermal imaging night vision	Thermal imaging night vision	Thermal imaging of PWBs