FLEXIBLE X-RAY DETECTOR BASED ON THE SEEBECK EFFECT

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ABSTRACT

In this article, a theoretical and experimental basis for a new x-ray detector concept based in the conversion of x-rays into thermal energy is presented. The detector follows an indirect approach, once the x-rays are first converted into thermal energy, which is then converted into electrical signals by the Seebeck effect. The detector does not need high operating voltages as the detectors based in photoconductors, and it shows higher efficiency in the energy conversion than the x-ray detectors based in scintillators. Moreover, this technique allows the fabrication of x-ray detectors on flexible substrates, which is not possible with the other methods.

KEYWORDS

Flexible sensor, x-ray sensor, Seebeck x-ray, digital radiography.

INTRODUCTION

X-rays can be converted into electrical signals by two main approaches, known as direct and indirect methods. Independently of the used method, to achieve an x-ray image (radiography) it is necessary to place many x-ray detectors in array disposition. In the direct method, the x-ray detectors are usually based in photoconductors. In the indirect method, scintillators associated to photodetectors are typically used. Each x-ray detection method has its performance advantages and limitations on its use for practical x-ray image detectors.

The direct method based in photoconductors uses photoconductive materials with high x-ray absorption capability. These materials can be placed on an array of conductive charge collection plates, each of them supplied with a storage capacitor. There are some devices based on photoconductors such as CdTe, CdZnTe, HgI_2 and PbI_2 [1, 2, 3]. The readout electronic circuitry must be developed in a separate die due to incompatibilities between the two fabrication processes. Moreover, for the operation of these devices, a high-voltage is necessary for biasing the photoconductors.

The indirect method uses materials that absorb x-rays and convert its energy into visible light, which is easily detected by silicon photodetectors, for example [4, 5]. These materials, known as scintillators, usually consist on compounds constituted by elements of high atomic number, which have high x-ray absorption capability, and yield many visible light photons for each absorbed x-ray quantum.

The main drawback of this configuration is its low energy efficiency, especially for detectors with small dimensions or detector arrays with small pixel sizes [6]. This low efficiency is due to large losses in the energy conversions from x-rays to visible light and from visible light to electrical current. The energy lost is dissipated in the form of heat.

Both the direct and indirect methods described above are developed on rigid substrates (usually silicon panels), which can be considered as a drawback for some applications.

To avoid the previously presented drawbacks, this work shows a device that does not need high bias voltages as the photoconductors, and has higher energy efficiency than the scintillators. The efficiency is increased by converting the x-rays into thermal energy, which is then detected by means of the Seebeck effect. Moreover, with this technique it will be possible to fabricate x-ray detectors on flexible substrates.

VALIDATION OF THE WORKING PRINCIPLE

The working principle of the x-rays detector based on the Seebeck effect consists in detecting the increase in temperature caused by absorption of the x-rays by a material with high atomic number and high-density. A junction of two materials with different Seebeck coefficients is used to detect the increase in temperature.

Figure 1 shows the basic structure of an x-ray detector based on the Seebeck effect. It consists on a plate (copper for example), which works as x-ray absorbing material, where two wires with different Seebeck coefficients are connected.

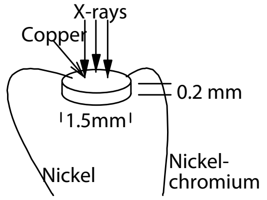

Figure 1: Structure of the x-ray detector. When the x-ray photons reach the copper plate, its temperature increases. Further, the Ni-NiCr thermocouple junction will detect the temperature change and convert it into an electrical signal.

The theoretical analysis of the detector can be divided into three sections: the x-ray source; absorption of x-rays; conversion of x-rays into heat and detection of temperature changes.

X-ray source

The x-ray source used in our experiments works with a voltage of 35 kV and a current that can range from 0 to 1 mA. That means that the maximum electrical power absorbed by the x-ray source is 35 W. The efficiency of the x-ray production can be defined by the rate of kinetic energy of the electrons that is converted into x-rays. The efficiency η is directly proportional to the atomic number of the material used as anode in the x-ray source (Z) and to the electrical voltage applied between the anode and the cathode (V):

$$\eta = KZV \tag{1}$$

where $K \approx 1\times10^{-6}\ \mathrm{V}^{-1}$ [7]. For an x-ray source with molybdenum anode (Z=42) and an electrical voltage of 35 kV, the efficiency is approximately equal to 1.47×10^{-3}. As a result, the power of the produced x-rays is just 51.45 mW.

According to the electromagnetic theory, to a charged particle acceleration corresponds the production of an electromagnetic wave, which travels in a direction perpendicular to the acceleration. This means that the produced x-rays will travel in all directions in a plane perpendicular to the direction of the electrons. According to classical physics, an electron accelerated by a 35 kV potential acquires a velocity of $1.11\times10^{8}\ \mathrm{m\,s}^{-1}$, which is more than one third of the speed of light. Relativistic effects appearing due to these velocities are not taken into account in the present calculation. Figure 2 shows a target with 1 mm^2 size, placed in the plane of the x-rays at a distance of 10 cm from the x-ray source.

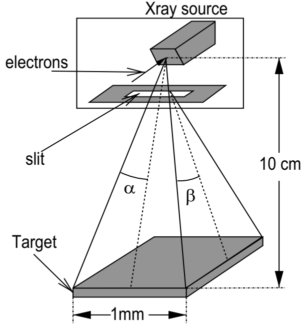

Figure 2: Maximum angle at which the x-rays can be absorbed by the target.

The maximum angle α at which the x-rays can be absorbed by the target can be obtained from:

$$\alpha = \arctan\frac{0.5\times10^{-3}}{10\times10^{-2}} = 0.286^{\circ} \tag{2}$$

As the x-rays are produced randomly in the tube, with equal probability in any direction perpendicular to the beam of electrons that originates them, the ratio between the x-rays arriving at the target and the ones that are produced by the source is $2\alpha/360^{\circ}$, that is, 1.592×10^{-3}. The power of the x-rays arriving at the target will be just $51.45\times10^{-3}\times1.592\times10^{-3}$ = 88.88 μW.

The former calculation has been performed in one dimension, as the dispersion produced by the slit in the x-ray tube (which has 0.9 mm of thickness) does not produce significant effects at a distance of 10 cm.

Absorption of x-rays

When penetrating into a material layer, a beam of x-rays is absorbed according to an exponential law:

$$I = I_o e^{(-\mu/\rho)\rho x} \tag{3}$$

where I_o is the initial intensity of the beam, I is its intensity at a distance x from the surface and ρ is the density of the material. The ratio (μ/ρ) is the mass absorption coefficient of the material and can be found in tables like the one published by Hubbell [8].

Applying equation (3) to a copper plate of 0.2 mm of thickness, it is possible to calculate that 99.739% of the incident x-ray photons of 20 keV of energy (which is approximately the energy peak produced by a 35 kV x-ray tube) will be absorbed. Figure 3 shows a simulation graph of the percentage of x-rays absorbed by a copper plate as a function of its thickness.

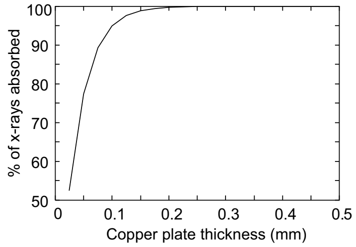

Figure 3: Percentage of 20 keV x-ray photons absorbed by a copper plate as a function of the plate thickness.

Conversion of x-rays into heat and detection of temperature changes

The x-rays that are absorbed by the target material of the detector will heat it. The corresponding temperature change is obtained from:

$$Q = cm\Delta T \tag{4}$$

where Q is the energy of the absorbed x-rays, c and m are the specific heat capacity and the mass of the target, and ΔT is the temperature change. Table 1 shows the atomic number, the density and the specific heat capacity of some metals.

Table 1: Atomic numbers, densities and specific heat capacities of some metals at 300 K [9].

	Atomic Number	Density ($g\ cm^{-3}$)	Specific Heat Capacity ($J\ g^{-1}\ K^{-1}$)
Aluminum	13	2.7	0.897
Iron	26	7.8	0.450
Copper	29	8.96	0.385
Silver	47	10.5	0.235
Platinum	78	21.4	0.135
Gold	79	19.3	0.1291
Lead	82	11.3	0.125

In order to stop and absorb the x-ray energy it is necessary a material with high atomic number and density (eq. (3)). On the other hand, to obtain higher temperature changes, it is more appropriate a material with low mass and low specific heat capacity (eq. (4)). Copper is a material that better satisfies both the requirements.

A copper target has a specific heat capacity of $0.385\,\mathrm{J\,g^{-1}K^{-1}}$ and a density of $8.96\,\mathrm{g\,cm^{-3}}$ at $300\,\mathrm{K}$. The mass of the target (figure 1) is 1.792 mg in our case.

The energy of the x-rays that are absorbed by the copper plate during 1 second is 81.88 μJ. In this case, ΔT would be equal to 118.7 mK. At this point we have neglected the effect of the power dissipation to the environment that surrounds the target.

A type K thermocouple produces a potential difference of $39.7\,\mu\mathrm{V/K}$, for temperature differences near $0\,\mathrm{K}$ between its hot and cold junctions. In this case, the temperature of 118.7 mK will produce a voltage of 4.711 μV. This is the order of magnitude of the values expected in our experiments.

Experimental validation

In order to validate the theory, a simple detector like the one depicted in figure 1 was built. An x-ray tube was powered with a voltage of 35 kV and a current ranging from 0 to 1 mA (input power ranging from 0 to 35 W). As calculated above, this means that the x-ray power reaching the target material of the detector will range approximately from 0 to 88.88 μW. The results are presented in figure 4.

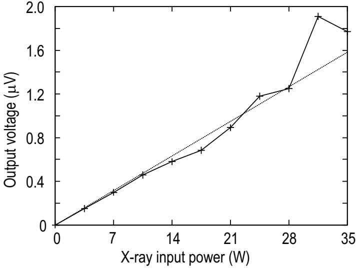

Figure 4: Measurements obtained with the type K thermocouple test device: The x-ray tube was powered with a voltage of 35 kV and a current ranging from 0 to 1 mA (input power ranging from 0 to 35 W).

As it can be observed in figure 4, the measured values are a lower than the expected ones. This is due to the power dissipation to the surrounding environment of the detector and thermal losses through the substrate and thermocouple wires. The relativistic effects in the x-ray production decrease the x-ray power too. By coating the detector target with a low-density thermal insulating material can reduce the dissipation. Different dimensions of thermocouples can also reduce thermal losses. It can be also observed in figure 4 that there is a linear relationship between the output voltage generated in the thermocouple and the x-ray input power.

FABRICATION OF THE DETECTOR

After the positive result in the previous experiment, an x-ray detector was fabricated on a flexible polyimide Kapton© substrate

Thermoelectric p-type (Sb_2Te_3) and n-type (Bi_2Te_3) thin films with thickness up to 10 μm and high figures of merit were obtained by a thermal co-evaporation method [10] in a high-vacuum chamber.

The substrate temperature and evaporation rates were controlled during all the deposition process in order to obtain the desired properties. The thermoelectric properties obtained -Seebeck coefficient of -248 μV/K and +188 μV/K in n-type and p-type respectively and electrical resistivities in the range 10-20 μΩ m- make these materials suitable for the fabrication of thermal elements. Table 2 summarizes the thermoelectric properties, namely the Seebeck coefficient, the resistivity and the figure of merit (ZT) at 300 K, which is defined as:

$$ZT = \frac{\alpha^2}{\rho\lambda}T \tag{5}$$

where α is the Seebeck coefficient, ρ the electrical resistivity, λ the thermal conductivity and T the temperature [11].

Table 2: Summary of the thermoelectric properties of Bi_2Te_3 and Sb_2Te_3.

Film	Te	Bi or Sb	Seebeck ($\mu V\,K^{-1}$)	Resistivity ($\mu\Omega$ m)	Fig. Merit (300 K)*
Bi_2Te_3	62%	38%	-248	12.6	0.86
Sb_2Te_3	73%	27%	188	12.6	0.49

**Thermal conductivity of 1.7 $Wm^{-1}K^{-1}$ was assumed on calculations*

The thermoelectric elements were connected to metal contacts, fabricated on the substrate by deposition of a 800 nm layer of aluminum covered with a thin layer of Nickel (20 nm). Thermoelectric films were deposited on the top of the contacts. These films were patterned during the evaporation process using shadow masks. In this way a thermoelectric device was fabricated.

Polyimide was chosen as substrate because of its low thermal conductivity ($0.16\,\mathrm{W\,m^{-1}K^{-1}}$), thus allowing higher performance of the devices, even with higher values of substrate thickness (12 μm foil was used). Finally, a copper plate of 100 μm was placed on top of the thermoelectric materials (figure 5).

Figure 5: Picture of the fabricated device.

EXPERIMENTAL RESULTS

In order to verify experimentally the performance of the flexible fabricated device, the x-ray tube was powered with a voltage of 35 kV and a current ranging from 0 to 1 mA. The obtained voltage is shown in figure 6.

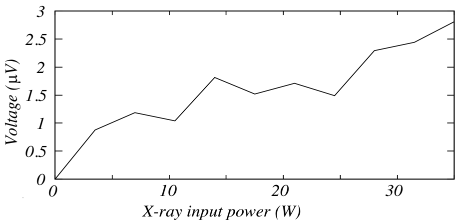

Figure 6: Experimental results: output voltage by increasing input power. The x-ray tube was powered with a voltage of 35 kV and a current ranging from 0 to 1 mA.

Similar to the previously reported results with a type K thermocouple, this device also has lower performance than expected. Despite radiation and convection losses previously described, device performance is also reduced by thermal losses through substrate and thermoelectric sensor films. Together with coating the detector, different dimensions of thermal sensors can also reduce thermal losses. The thickness of the used copper plate, which is half the one used with the K thermocouple also influences the results.

Another test was made, consisting in powering the x-ray tube with 35 kV / 1 mA and manually switching on and off in order to produce an x-ray pulse each 10 s. The results are presented in figure 7.

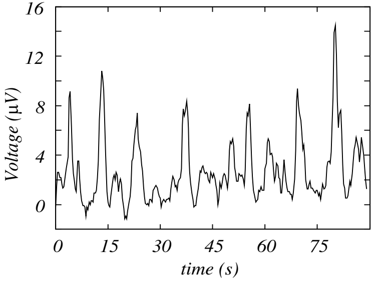

Figure 7: Voltage measured at the detector terminals when the x-ray tube was powered with 35 kV and 1 mA and manually switched on and off, in order to produce an x-ray pulse each 10 s.

The lower voltages obtained in the previous test (3 μV in figure 6) compared to this on/off test (10 μV in figure 7) are due to the slow thermal response of the system, that also heats the cold junction of the thermal sensor (which was considered at room temperature in calculations), but at a slower rate that the absorber itself, when the x-ray absorber is continuously heated. Despite the aforementioned issues, the previously presented results, nearly increasing output voltage for increasing x-ray input power (figure 6) and pulsed output voltage for pulsed input x-rays (figure 7), validate the present approach and the suitability of the detector for x-ray applications.

CONCLUSIONS

In the present work the Seebeck effect was used in the detection and measurement of x-ray signals. The constructed device does not need high-bias voltages to work properly as in the case of the photoconductors and it shows larger energy conversion efficiency than the detectors based on scintillating crystals. Moreover, it was fabricated on a flexible substrate, adding interest for potential applications in digital radiography. Since the working principle of the detector is based on temperature changes, the main drawback of this approach is the low frequency response. This could be overcame by using a smaller volume sensor and active cooling by Peltier effect on the thermoelectric sensors elements.

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