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Active thermal-electronic devices based on heat-sensitive metal-insulator-transition resistor elements

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ABSTRACT

New active thermal-electronic device family is proposed. These devices operate by means of thermal (or hot electron) coupling between adjacent domains containing heating (input) and thermally sensitive (output) elements. The theoretical background, basic equations and comparison with the conventional electron devices are the main subject of this work. According to the theoretical assumptions the realization of the thermal-electronic device needs a very sensitive output element *i.e.* temperature sensor. Among others, the metal-insulator transition (MIT) based resistor fulfills this requirement. The MIT resistor itself has got thyristor-like I–V characteristics due to solely the high electric field, or Joule heating induced extremely strong step-like resistance drop at a given temperature. Using thermally coupled MIT and/or other resistors it is possible to build a special device, namely phonsistor (=phonon transistor). This device consists of only bulk type intrinsic domains, containing significantly fewer regions, junctions, depleted layers, surfaces and interfaces compared to conventional electron devices. Thus, these devices can be integrated together with each other and with conventional CMOS, forming, for example, thermal-electronic logic circuit (TELC) for the More-Than-Moore concept devices.

1. Introduction

The “sensor cube” was introduced in the last century for proper classification of different sensor constructions. It is not a real cube, rather a three-dimensional transducer effects diagram. Two axis define the powering and output signal carrying energy forms, the third one represents the modulating effects. Each axis has got six different forms of energy or excitation: radiative, mechanical, thermal, electrical, magnetic and chemical. The different sensor and transducer devices and functions can be defined briefly by means of formalism similar to the Miller indices used in crystallography: [*powering* energy form, *output* energy form, *modulation* carrying energy]. For example the solar cell converts the *rad*iative light energy to *elect*rical energy without modulation, thus its place in the sensor cube is [*rad., elect., 0*]. Photoconductor, piezo resistor, thermo-resistor indices are [*elect., elect., rad*], [*elect., elect., mech.*], [*elect., elect., therm.*], respectively, as they need *elect*rical powering energy, their output signal is *elect*rical, which is modified by *rad*iative, *mech*anical and *therm*al energy [1]. Most solid state electron devices can be classified simply as [*elect., elect., elect.*], because they need electrical energy from the power supply and the output electrical signal is controlled or modulated by the electrical signal on the input (modulating) electrode of the device. However, the sensor cube formalism provides a chance to describe the device operation in details. In the case of the bipolar transistor which is composed of a forward biased minority charge carrier emitting *np* junction and a minority carrier sensitive reverse biased *pn* junction as collector, the detailed indices are [*0,chem., elect.*] [*elect., elect., chem.*]. In this approach the electro*chem*ical potential (quasi Fermi level) is modulated in the base by an *elect*rical signal on the emitter, the output is *elect*rically powered, and the output *elec*trical current is modulated by the electro*chem*ical potential in the base.

The bases of our new active thermal-electronic device family are heating (input) and thermally sensitive (output) elements, thermally coupled. [*0,therm., elect.*] is valid for the Joule heating resistive element producing *ther*mal output signal modulated by *elect*rical input, while [*elect., elect., therm.*] is for the *elect*rically powered *therm*ally sensitive element with *elect*rical signal at the output, thus for the complete system the operation can be summarized as [*0,therm., elect.*] [*elect., elect., therm.*].

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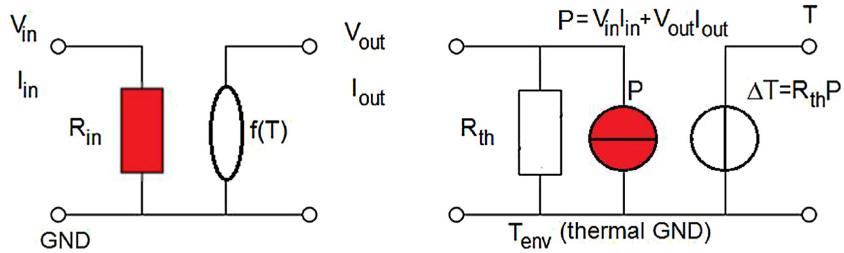

Fig. 1. Electrical and thermal equivalent circuits of thermal-electronic devices. The sensor is characterized by a transducer function *f(T)* resulting in V_{out} or I_{out}, depending on the form of electrical excitation on the output, i.e. the type of power supply.

2. The thermal-electronic device in general

The schematic structure (equivalent circuits) of the thermal-electronic device is shown in Fig. 1. The input heating element (R_{in}) and output temperature sensitive element (*f(T)*) are close to each other (i.e. the thermal coupling is strong), thus the thermal resistance between them is much less than the thermal resistance between the system and the environment (R_{th}).

Electrical signal on the input results in temperature increase with respect to the thermal ground, i.e. the environmental temperature (T_{env})

$$T - T_{env} = \frac{V_{in}^2}{R_{in}} R_{th} \quad (1(a))$$

or

$$T - T_{env} = I_{in}^2 R_{in} R_{th} \quad (1(b))$$

when it is assumed that the heat energy required for temperature sensitive element *f(T)* to operate is much less than the heat energy lost to the heating of the thermal ground, and furthermore, system is studied with respect to unit time response. Subsequently,the most important small signal electrical parameters (current gain, β, transfer admittance, g_m, voltage gain, A) can be described using their definitions and derivatives of (1(a)) or (1(b)):

$$\beta = \frac{\partial I_{out}}{\partial I_{in}} = \frac{\partial I_{out}}{\partial T}\frac{\partial T}{\partial I_{in}} = 2 I_{in} R_{in} R_{th} \frac{\partial I_{out}}{\partial T} \quad (2(a))$$

$$g_m = \frac{\partial I_{out}}{\partial V_{in}} = \frac{\partial I_{out}}{\partial T}\frac{\partial T}{\partial V_{in}} = 2 V_{in} \frac{R_{th}}{R_{in}} \frac{\partial I_{out}}{\partial T} \quad (2(b))$$

$$A = \frac{\partial V_{out}}{\partial V_{in}} = \frac{\partial V_{out}}{\partial T}\frac{\partial T}{\partial V_{in}} = 2 V_{in} \frac{R_{th}}{R_{in}} \frac{\partial V_{out}}{\partial T} \quad (2(c))$$

It can be concluded from the equations above, that any temperature sensitivity may result in amplification, but high thermal resistance and sensitive output are necessary to get high current/voltage gain and transfer admittance. The thermal resistance is related to the effectiveness of the input transducer, because the heating resistor on thermally isolated domain results in a higher temperature shift. The temperature derivatives ($\partial/\partial T$) of output electrical responses (V_{out}, I_{out}) describe the temperature sensitivity of the output thermal sensor.

The voltage gain can be expressed with the ratio of the output and input electrical resistances of the electron devices. In the case of thermal-electron devices the ratio of thermal resistance and the input electrical resistance (R_{th}/R_{in}) plays similar roles.

3. Practical realization of the thermal-electronic devices

There are many different way to realize the thermal-electronic device, as both the input and output elements can be varied. Any temperature controlled device, *e.g.* thermoelectric generator, forward biased *pn* junction, or semiconductor resistor may act as output heat-sensing element, as long as it's electrical output signal can be modulated by the heat from input element.

The first functional thermal-electronic device was developed fifty years ago [2]. Three diffused heating resistors were integrated with aluminum (Al) contacted thermoelectric sensors on a silicon (Si) substrate, which resulted in a 4-quadrant analogue multiplier with relatively low voltage gain and several kHz cutoff frequency. This kind of thermal-electronic device does not need a power supply; it can be characterized as [*0,therm., elect.*] [*0,elect., therm.*] notation. The $V_{out}=f(V_{in})$ transfer function in Eq. 4(a) is parabolic, and depends on the Seebeck coefficient *S*, the number of sensors in series connection *N*, and the above mentioned thermal resistance/input resistance ratio (R_{th}/R_{in}). The voltage gain in Eq. 4(b) is either the differential of Eq. 4(a), or either N × Eq. 2(c), in which the last term is Seebeck coefficient. As this device operates without power supply, the power gain is lower than one; however, a suitable construction may result in a remarkable voltage gain.

$$V_{out} = V_{in}^2 NS \frac{R_{th}}{R_{in}} \quad (4(a))$$

$$A = \frac{\partial V_{out}}{\partial V_{in}} = 2 V_{in} \frac{R_{th}}{R_{in}} NS \quad (4(b))$$

Similar equations were derived earlier for pn junctions having forward bias by current generator and that was coupled with a heating resistors by notation [0,therm., elect.] [elect., elect., therm.] [3]. The pn-junction voltage shifts about 2 mV/°C in the case of forward bias, and thus the product ($N \times S$) could be replaced with this shift in Eqs. 4(a) and 4(b).

As it can be seen from the equations above, the previously discussed possibilities are theoretically suitable for construction of thermal-electronic devices. However, as the sensitivity of the output device is not very high, the amplification could be increased only by proper thermal isolation for high R_{th} value.

Heat-sensitive resistors, especially the resistors capable to perform the reversible metal-insulator transition (MIT) as a function of temperature, promise excellent possibilities to realize good quality thermal-electronic devices, because of their strong temperature dependence of the resistance [4]. One such a material with reversible MIT effect is vanadium oxide (VO_2) performing even up to five decades MIT at around the transition temperature $T_{MIT} \approx 68\,°C$ [5]. Integrated nanostructured, horizontal or vertical resistors with, *e.g.* platinum (Pt) contact electrodes, to form a simple Pt/VO_2/Pt resistor structure can be easily fabricated with novel microelectronics and nanotechnology methods [6]. In Fig. 2, there is an example of a lateral Pt/VO_2/Pt resistor MIT effect with around three decades transition shown.

The integrated heating resistor – MIT capable sensing resistor system is patented as phonsistor (=phonon transistor) [7]. The schematic structure and equivalent circuits are shown in Fig. 3. Examining active electron devices in general, such as transistors, it is possible to find many common features and analogies between these systems. Inputs and outputs are coupled in different ways,