Dynamics of Long-Wave Infrared Range Thermocouple Detectors

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Abstract

Infrared detectors for the long-wave infrared range (LWIR) based on nano structured thermocouples exhibit response times in the order of picoseconds and will open new areas of applications in THz broadband communication systems. We investigate the thermal dynamics of nano-thermocouples for a substrate heated by a nano structured thermocouple patch. Due to its low thermal capacity a mesoscopic thermocouple is an extremely fast square-law detector with cutoff frequencies up to several hundred GHz.

1 Introduction

Infrared detectors for the long-wave infrared range (LWIR) are already used for radiometry and thermal imaging. A promising novel concept for LWIR detectors is the combination of a nanoantenna with a rectifying element [1, 2]. Frequency selective LWIR detectors for 28.3 THz were realized as antenna-coupled nano-wire thermocouples constructed from a dipole antenna and a nano-wire thermocouple with the hot junction located at the center of the antenna [3]. Such detectors exhibit response times in the order of picoseconds and will open new areas of applications in THz broadband communication systems [4]. In this work, we investigate the thermal dynamics of nano-thermocouples by solving the time-dependent heat equation for a substrate heated by a nano structured thermocouple patch. Due to its low thermal capacity a mesoscopic thermocouple is an extremely fast square-law detector with cutoff frequencies up to several hundred GHz.

2 Seebeck Effect Based Thermoelectric Detection

Thermocouple LWIR detectors are based on the Seebeck effect. The RF electric field is accelerating the electrons in the electron gas of the thermocouple metals. The Joule heating of the thermocouple occurs through the interaction of the electrons with the lattice vibrations of the metal and in case of thin metallic layers also with the lattice vibrations of the substrate [5, 6]. For the Seebeck effect the elevation of the electron temperature is relevant. When the thermocouple dimensions are considerably larger than the electron-electron relaxation length, the electrons are distributed according to the Fermi-Dirac statistics. Assuming a scalar Seebeck coefficient S, the relation between the variation of the Seebeck voltage v_S and the gradient of the temperature T is given by

$$\nabla v_S = -S \nabla T \,. \tag{1}$$

The Seebeck coefficient S is given for metals by the Mott relation [7, 8]. Thermocouples fabricated from two conductors A and B with different Seebeck coefficients S_A and S_B, respectively, and containing two junctions exhibit an open-circuit seebeck voltage v_S

$$v_S = \Delta T (S_A - S_B) \,, \tag{2}$$

if a temperature difference ΔT is maintained between the two junctions.

If a mesoscopic thermocouple on the basis of the Seebeck effect with dimensions in the order of some ten nanometers is used, the electron temperature should be raised in the junction area within a volume the extension of which presumably is determined by the diffusion length. Hence, it is reasonable to collect the incident radiation with an antenna and to concentrate the electron heating in a small volume. The dissipated radiation will first raise the electron temperature. The thermal energy will be passed over to the lattice and from there further passed over by conduction and/or radiation to the environment.

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3 The Thermal Conduction in the Thermocouple Substrate

Figure 1 shows the cross sectional view through a substrate of thickness d with a circular metallic patch of radius r_0. In the following we will investigate the thermal pulse response of the substrate region under the patch for an impulsive heating of the patch. Consider the partial differential equation describing the heat

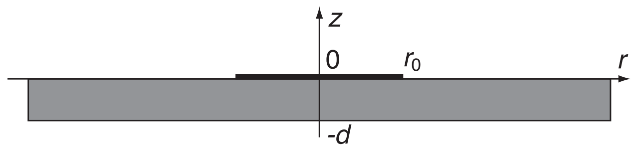

Figure 1: Cross sectional view through through the disk with heated patch.

conduction in the cylindrical coordinate system r, ϕ, z,

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}\,, \tag{3}$$

where t is the time, $T(r, \phi, z, t)$ is the temperature, and α is the thermal diffusivity given by $\alpha = k/\rho c_p$, where k is the thermal conductivity, ρ is the density, and c_p is the specific heat of the material [9]. We assume cylindrical symmetry of the problem, so that the temperature is independent of ϕ. With the separation of variables in the form

$$T(r, z, t) = R(r)Z(z)g(t) \tag{4}$$

we obtain from (3)

$$\frac{1}{R}\left[\frac{d^2 R}{dr^2} + \frac{1}{r}\frac{dR}{dr}\right] + \frac{1}{Z}\frac{d^2 Z}{dz^2} = \frac{1}{\alpha}\frac{1}{g}\frac{dg}{dt}\,. \tag{5}$$

Since $R(r)$, $Z(z)$, and $g(t)$ are independent from each other, we can set each of the corresponding parts in this equation constant and obtain

$$\left[\frac{d^2 R}{dr^2} + \frac{1}{r}\frac{dR}{dr}\right] + \beta^2 R = 0\,, \tag{6a}$$

$$\frac{d^2 Z}{dz^2} + \eta^2 Z = 0\,, \tag{6b}$$

$$\frac{dg}{dt} + \alpha\lambda^2 g = 0\,, \tag{6c}$$

where the separation parameters β, η, and λ are related by

$$\lambda^2 = \beta^2 + \eta^2\,. \tag{7}$$

The particular solutions of (6a) - (6c) are

$$R(r) = J_0(\beta r)\,, \tag{8a}$$

$$Z(z) = \left\{\begin{array}{c} \sin\eta z \\ \cos\eta z \end{array}\right\}\,, \tag{8b}$$

$$g(t) = e^{-\alpha\lambda^2 t}\,. \tag{8c}$$

We have considered in (8a) only the Bessel functions of the first kind since these are non-singular at $r = 0$.

By superposition of the particular solutions we obtain the general solution

$$T(r, z, t) = \int_{\beta=0}^{\infty}\int_{\eta=0}^{\infty} \left[A(\beta, \eta)\sin\eta z + B(\beta, \eta)\cos\eta z\right] J_0(\beta r) e^{-\alpha\left(\beta^2+\eta^2\right)t} d\beta d\eta\,, \tag{9}$$

where β is the radial phase coefficient of the heat diffusion wave. The initial temperature distribution of the particular solution is given by

$$T(r, z, 0) = \int_{\beta=0}^{\infty} \int_{\eta=0}^{\infty} [A(\beta, \eta) \sin \eta z + B(\beta, \eta) \cos \eta z]\, J_0(\beta r) d\beta d\eta\,. \tag{10}$$

Consider a disk of thickness d and assume $z \in [-d, 0]$. In this case the continuous spectrum of η is replaced by the discrete spectrum $2\pi n/d$ with integer n, and we can expand $T(r, z, t)$ in z direction into a Fourier series and obtain

$$T(r, z, t) = \sum_{n=-\infty}^{\infty} \int_0^{\infty} C_n(\beta) e^{\frac{2\pi \jmath n z}{d}} J_n(\beta r) e^{-\alpha\left[\beta^2 + \left(\frac{2\pi n z}{d}\right)^2\right] t} d\beta, \tag{11}$$

where we have replaced the real coefficients $A(\beta, \eta)$ and $B(\beta, \eta)$ by the complex Fourier coefficients $C_n(\beta)$, satisfying $C_{-n}(\beta) = C_n^*(\beta)$. The partial wave with the radial wave coefficient β and the vertical wave index n decays with a time constant

$$\tau_n(\beta) = \frac{1}{\alpha\left[\beta^2 + \left(\frac{2\pi n z}{d}\right)^2\right]}\,. \tag{12}$$

To give a rough estimate of the time constant for the decay of the local heating under the patch with radius r_0 in Figure 1 we consider the partial wave with $n = 0$ where the radial part $J_0(\beta r)$ exhibits the first zero at $r = r_0$, i.e. for $\beta = 2.405\, r_0^{-1}$. The time constant computed from (12) on the basis of this assumption is proportional to r_0^2. For $r_0 = 25$ nm we obtain a time constant of 1.19 ps and for $r_0 = 10$ nm a time constant of 0.19 ps. This shows that a mesoscopic thermocouple is an extremely fast square-law detector with cutoff frequencies up to several 100 GHz.

The initial temperature distribution is given by

$$T(r, z, 0) = \sum_{n=-\infty}^{\infty} \int_{\beta=0}^{\infty} C_n(\beta) e^{\frac{2\pi \jmath n z}{d}} J_0(\beta r) d\beta\,. \tag{13}$$

To compute the thermal pulse response for the disk shown in Figure 1 we assume that at time $t = 0$ the patch is impulsively heated such that the temperature under the patch is raised within an infinitely thin layer at $z = 0$ and uniformly in the region $0 \le r \le r_0$. So we choose the initial condition

$$T(r, z, 0) = \delta(z)\, \sigma(r_0 - r)\,. \tag{14}$$

From this, $C_n(\beta)$ can be computed by Fourier expansion for the z dependance and inverse Hankel transform for the radial dependance. We have to consider that the thermal analysis at dimensions in the nanometer scale deals with sub-continuum phenomena as ballistic electron transport since the structure dimensions are in the order or less than mean free paths of the electrons (5 - 10 nm) and the phonons (200 - 300 nm) in bulk silicon at room temperature [5]. Therefore classical diffusion theory predictions in heat conduction may not be applicable.

4 The Equivalent Circuit of the Thermocouple

Figure 2 shows the equivalent circuit of a thermocouple fed by a small antenna [4]. The equivalent circuit consists of an electric RF part, a thermal part and an electric low frequency part. The complex envelope v_{RF} of the open circuit RF voltage of the antenna is given by

$$v_{RF} = h_{eff} E_{inc}\,, \tag{15}$$

where E_{inc} is the amplitude of the incident electric RF field, h_{eff} is the effective antenna length. R_A, C_A and L_A describe the antenna impedance. The RF impedance of the thermocouple is characterized by the junction resistance R_j in parallel with the junction capacitance C_j.

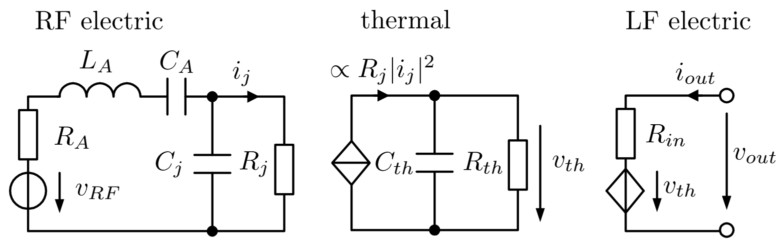

Figure 2: Equivalent circuit of antenna with thermocouple [4].

The dissipated power, $R_j|i_j|^2$, is heating the junction and increases the junction temperature by ΔT. The thermal properties of the junction are characterized by the thermal capacitance C_{th} and the thermal resistance R_{th}. The thermo voltage v_{thc} is given by

$$v_{th}(t) = k \int_{-\infty}^{t} i_j^2 e^{-\frac{t-t_1}{\tau_{th}}} \, dt_1 \,, \tag{16}$$

where τ_{th} is the thermal time constant. In the equivalent circuit $v_{thc}(t)$ is modeled by the controlled voltage source v_{thc}. The thermal time constant can be modeled by R_{th} and C_{th} with $R_{th}C_{th} = \tau_{th}$. This yields in an open circuit thermo voltage v_{th}, which, in turn, can be observed as the output voltage

$$v_{out} = v_{th} + R_{in} i_{out}, \tag{17}$$

where i_{out} is the load current driven by of the thermo voltage source v_{th}.

5 Conclusion

The thermal dynamics of nano-thermocouples have been investigated for a substrate heated by a nano structured thermocouple patch. This theoretical investigation shows that extremely fast square-law detectors with cutoff frequencies up to several hundred GHz are possible due to the low thermal capacity of a mesoscopic thermocouple.

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