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Parameterized Simulation Program with Integrated Circuit Emphasis Modeling of Two-level Microbolometer

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Abstract - This paper presents a parameterized simulation program with integrated circuit emphasis (SPICE) model of a two-level microbolometer based on negative-temperature-coefficient thin films, such as vanadium oxide or amorphous silicon. The proposed modeling begins from the electric-thermal analogy and is realized on the SPICE modeling environment. The model consists of parametric components whose parameters are material properties and physical dimensions, and can be used for the fast design study, as well as for the co-design with the readout integrated circuit. The developed model was verified by comparing the obtained results with those from finite element method simulations for three design cases. The thermal conductance and the thermal capacity, key performance parameters of a microbolometer, showed the average difference of only 4.77% and 8.65%, respectively.

Keywords: Microbolometer, Parameterized, SPICE, Modeling

1. Introduction

Microelectromechanical system technology allows creation of a microbolometer that is smaller, cheaper, and more sensitive; thus, the related market has rapidly expanded from the military to the medical, automotive, security and surveillance, and so on [1]. Among several structures [2-5], the two-level microbolometer structure developed by Honeywell is used worldwide. This structure consists of a metallic reflector on a silicon (Si) substrate, including the readout integrated circuit (ROIC), to increase the infrared (IR) absorption and an upper silicon nitride (SiN) plate containing the negative temperature coefficient (NTC) thin film resistor [5]. The nitride plate, which is a sandwich structure of SiN, leg metal, and SiN, is suspended over the Si substrate using two legs. The leg metal connects NTC resistor to the ROIC electrically. The NTC resistor is typically made of vanadium oxide (VO_x) or amorphous silicon (α-Si), and its resistance is decreased when the temperature of the device is increased because of IR absorption.

For the successful development of a microbolometer, a coupled physics analysis is necessary to consider the interaction between thermomechanics and electrostatics. Thus, three-dimensional, coupled physics finite element method (FEM) simulations are necessary [6]. Although this technique provides accurate and graphical results, studying the effects of design parameters, such as pixel size, critical width, temperature coefficient of resistance, and so on, is too time-consuming. To overcome this drawback, this paper presents a parameterized simulation program with integrated circuit emphasis (SPICE) model of a microbolometer. The proposed model consists of parametric components whose parameters are material properties and physical dimensions; thus, it can be used for fast design study, as well as for the co-design with the ROIC.

2. Thermal Operation

Microbolometer operation is based on the temperature increase caused by IR absorption. Some of the absorbed IR energy increases the device temperature, whereas the rest is dissipated into the substrate or its surroundings. To maximize the device sensitivity, minimizing the dissipated energy is necessary. Therefore, the device is designed as a thermal isolator. In other words, its thermal conductance should be restricted to the minimum level.

Three heat transfer mechanisms are involved: conduction, convection, and radiation. The most important heat transfer mechanism is conduction, and the absorbed IR energy can be conducted through two paths. One possible path is through the leg that supports the suspending SiN plate. The leg is unavoidable part of microbolometer; thus, it should be designed to have the minimum thermal conductance. The thermal conductance G can be calculated using Eq. (1):

$$G = \frac{Ak}{L} \tag{1}$$

where A is the cross-sectional area of the path, k is the thermal conductivity of the material, and L is the length of the path. Based on Eq. (1), the leg should have a small cross-sectional area, but long distance. Another thermal path is through the air surrounding the device. Specifically,

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the thermal path between the device and the underlying Si substrate is more important because it has shorter distance. The distance is fixed to the quarter-wavelength of the incident IR according to Fabry-Perot cavity resonance and the area is complexly connected to other performance parameters; therefore, the remaining control parameter is the thermal conductivity of the medium. The thermal conductivity of a gas is inversely proportional to the gas pressure; therefore, microbolometers are generally packaged in vacuum environment of <10 mTorr [7, 8]. As a result, thermal conduction through the surrounding medium can be ignored. The vacuum packaging also makes the thermal dissipation caused by the convection negligible. The last mechanism of radiation can be considered through the Stephan-Boltzmann law, which states that the thermal conductance due to the radiation is generally approximately an order of magnitude lower than that of the supporting legs [9]. As a result, only the heat conduction through the legs is included in the SPICE modeling, and radiation and convection are omitted.

Along with thermal conductance, thermal capacity is another key performance parameter in the microbolometer operation. The microbolometer consists of several thin films of SiN, NTC, and leg metal; thus, total thermal capacity C of the device is given as the numerical sum of thermal capacity of each material, as shown in Eq. (2):

$$C = \sum_i \rho_i V_i c_i \tag{2}$$

where ρ is the density, V is the volume, and c is the specific heat of each material, respectively.

Finally, the temperature T of a microbolometer is determined by the following heat balance equation:

$$C\frac{dT}{dt} + G(T - T_a) = Q \tag{3}$$

where T_a is the ambient temperature and Q is the absorbed IR power, respectively [9].

3. Parameterized SPICE Modeling

Considering the coupled physics nature of the microbolometer operation, the FEM simulation approach has been generally used in the device design. Although this approach can provide accurate and easy-to-understand graphical results, studying the effects of various design parameters is too time-consuming. In addition, this approach cannot be used when ROIC design is issued because the circuit design and simulations related with ROIC design need a high-level design environment such as VHDL, Verilog, or SPICE. As another approach, several SPICE models able to shorten the simulation time and applicable for the co-design with ROIC have been proposed [10-12]. Although these models are sufficiently strong to be used in the co-design with ROIC and the noise-related analysis, they have a critical limitation in that the parameters used in the model should be extracted experimentally. This means they cannot be applicable in the device design phase.

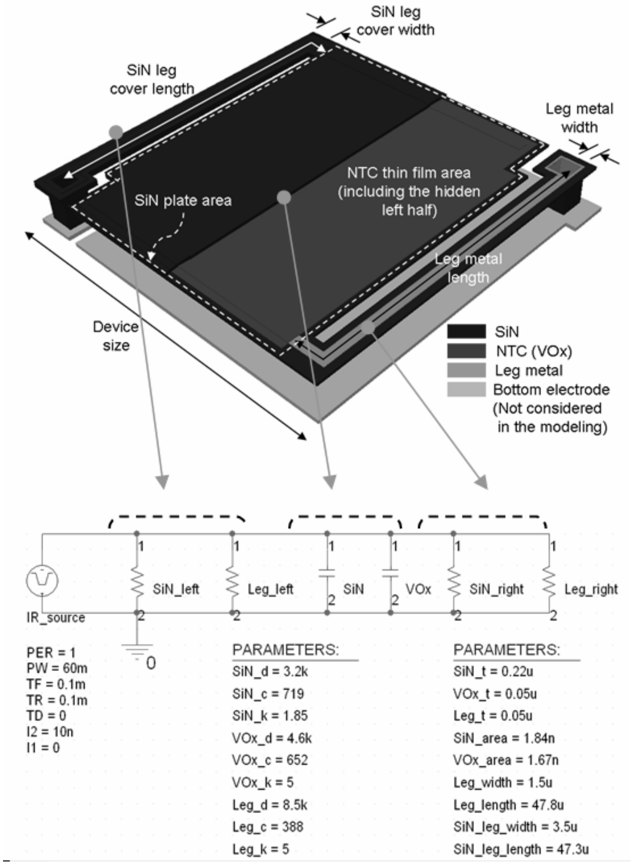


Fig. 1. Schematic view of the parameterized SPICE model.

Table 1. Material properties used in the modeling

	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)
SiN	3200	719	1.85
NTC film (VO_x)	4600	652	5
Leg metal (NiCr)	8500	388	5

The following parameterized SPICE modeling can be a solution for all these problems. It is sufficiently fast to be used in the design study because it is based on analytical models of the SPICE environment. All the parameters used in the model are material properties and physical dimensions; thus, the model does not need any experimental parameter extraction. Finally, the proposed model can directly interface with ROIC because ROIC can also be designed on the same SPICE environment.

Considering the thermal operation in Section 2, a parameterized SPICE model is presented in Fig. 1 with the corresponding microbolometer structure, where the right half of the top SiN layer is removed to reveal the underlying NTC thin film and the leg metal. The incident thermal energy can be stored in the detector because of the thermal capacity or flow out through two legs. Thus, the proposed model consists of two types of components: one is for the thermal conduction through two legs and the other is for the thermal capacity due to each material. The value of the thermal conduction was calculated with Eq. (1) and the thermal capacity with Eq. (2), with the material properties summarized in Table 1 [13] and the physical dimensions shown in Table 2. Laminated SiN and leg metal constitute the leg structure, and each material provides the separate channel for thermal dissipation. Therefore, the leg structure can be modeled as a two-resistor combination in parallel. Because the thermal capacity of multilayered structure is given as Eq. (2), the suspending plate can be modeled as parallel-connected capacitors representing each layer. Any additional parameter beyond those listed in Tables 1 and 2 is not required in the proposed model.

4. Verification of the Proposed Model

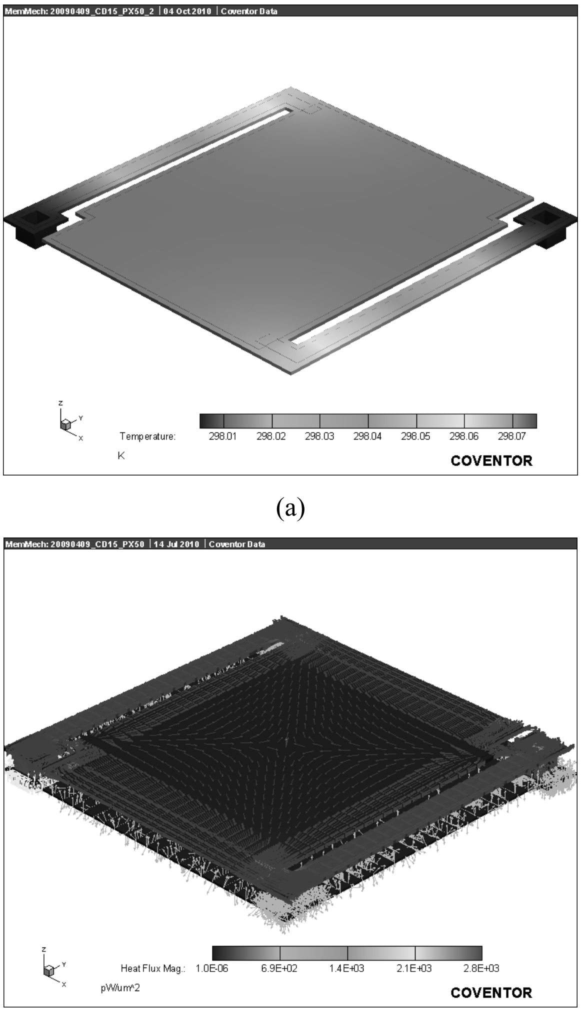
To verify the modeling accuracy, the results obtained with the parameterized SPICE model were compared with those from FEM simulations. Three types of design cases with different geometry were tested to determine whether the proposed model could be applicable for different designs. In splitting the designs, two key design parameters of the minimum pattern (i.e., width and the device size) were used. As the device size was changed, the IR absorption area and the leg length affecting the heat dissipation through Eq. (2) changed accordingly. As a result, the temperature rise of the device was also changed. With the same device size, the temperature rise could also be different if different minimum pattern widths were used. By using the smaller pattern width on the leg design, higher thermal resistance can be possible through Eq. (2); thus, temperature rise is more significant. Considering two design parameters, the design cases 1 and 2 are different in the minimum pattern width, whereas the design cases 2 and 3 are different in the device size.

Table 2. Physical dimensions for the three design cases

	Design 1	Design 2	Design 3
Min. pattern width (μm)	1.5	1.0	1.0
Device size (μm)	50	50	30
SiN thickness	0.22 μm		
NTC thin film thickness	0.05 μm		
Leg metal thickness	0.05 μm		
SiN plate area	1.84×10^{-9} m^2	2.03×10^{-9} m^2	0.645×10^{-9} m^2
NTC thin film area	1.67×10^{-9} m^2	1.89×10^{-9} m^2	0.564×10^{-9} m^2
Leg metal width (μm)	1.5	1.0	1.0
Leg metal length (μm)	47.8	47.1	27.1
SiN leg cover width (μm)	3.5	2.6	2.6
SiN leg cover length (μm)	47.3	47.5	27.5

FEM results were prepared with the commercial tool CoventorWare$^{\mathrm{TM}}$ (Fig. 2). In the FEM simulations, all the simulation parameters were assigned to be same as those in the parameterized SPICE model. As expected, the central plate absorbed the incident IR, and showed high temperature (Fig. 2a). Although some of the absorbed IR increased the temperature of the central plate, the rest were dissipated through two legs that worked as a thermal resistor (Fig. 2b).

Fig. 3 shows that the proposed model produced transient responses that matched well with those from FEM simulations, where IR power is assumed as incident for a moment and then removed. The key performance parameters of a microbolometer (i.e., the thermal conductance G and the thermal capacity C) can be extracted through the curve-fitting shown in Fig. 3 using Eq. (3).



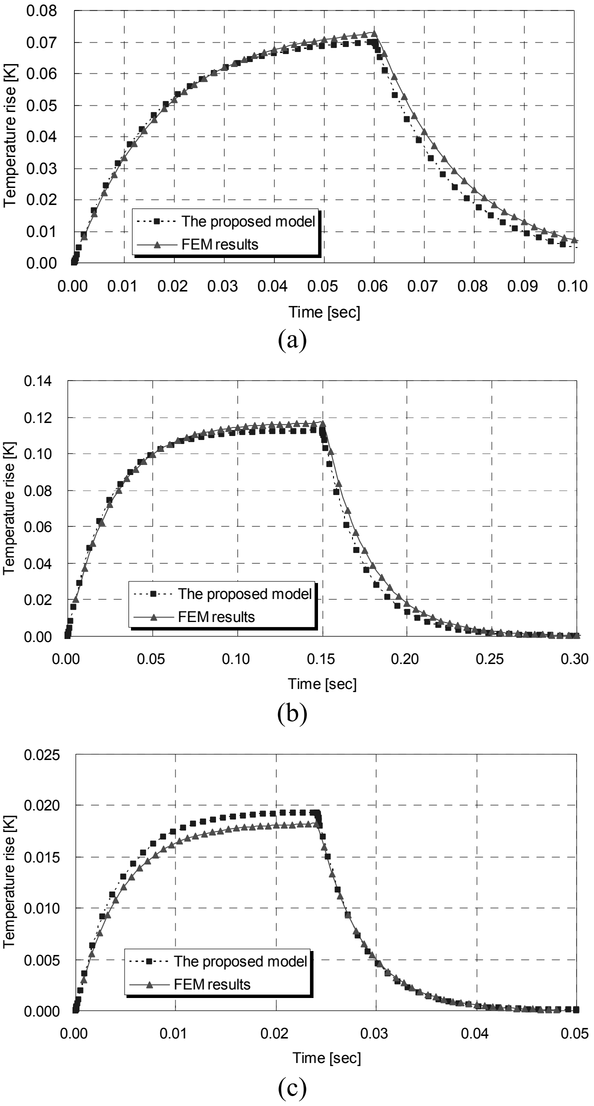
(a)

(b)

Fig. 2. (a) Temperature distribution and (b) heat flux of the design case 1 obtained by FEM simulation.

Table 3. Comparison results for the modeling accuracy

		Case 1	Case 2	Case 3
Simulation time	Proposed	0.05 s	0.02 s	0.03 s
	FEM	92 h 25 min 31 s	90 h 49 min 04 s	75 h 6 min 31 s
Thermal conductance G (W/K)	Proposed	1.40×10^{-7}	1.00×10^{-7}	1.75×10^{-7}
	FEM	1.34×10^{-7}	0.97×10^{-7}	1.85×10^{-7}
	Difference	4.94%	3.78%	5.58%
Thermal capacity C (J/K)	Proposed	2.11×10^{-9}	2.34×10^{-9}	7.37×10^{-10}
	FEM	2.28×10^{-9}	2.53×10^{-9}	8.26×10^{-9}
	Difference	7.34%	7.78%	10.8%



(a)

(b)

(c)

Fig. 3. Verification of the modeling accuracy of the parameterized SPICE model by comparing the simulation results to those from FEM simulations: (a) Design 1, (b) Design 2, and (c) Design 3.

The extracted parameters are summarized in Table 3. The average differences between the proposed model and the FEM were only 4.77% and 8.65%, respectively. Even with the similar results, the required simulation times were too dissimilar to be compared. FEM simulations require several tens of hours, whereas the simulations using the proposed SPICE model were completed in only seconds. All the simulations with the proposed model were completed in less than 1 s, whereas FEM simulations would have wasted several tens of hours. This simulation time is too long to be used to test various design candidates. Therefore, the proposed model can be used effectively to study various design candidates.

5. Conclusion

Parameterized SPICE model was developed for two-level microbolometer structure, where thermal conductance due to heat conduction in the supporting legs and thermal capacity in the constituting materials are included. The model consists of parametric components whose parameters are material properties and physical dimensions, and its results matched well with FEM simulation results for three design cases with different dimensions. The average differences between the results from the proposed model and the FEM approach were only 4.77% and 8.65% for the thermal conductance and the thermal capacity, respectively. With regard to the run time, the proposed model needs the simulation time of less than 1 s, whereas the FEM simulations requires several tens of hours. The proposed model has the advantages of (1) short simulation time compared to the FEM approach, (2) using parameterized components without experimental parameter extraction compared to the previous SPICE models, and (3) compatibility with ROIC design environment. Therefore, the proposed model can be used in the initial design study as well as in the co-design with the ROIC.

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References

[1] A. Rogalski, "Infrared detectors: status and trends," *Progress in Quantum Electronics*, Vol. 27, pp. 59-210, 2003.

[2] H.-K. Lee, J.-B. Yoon, E. Yoon, S.-B. Ju, Y.-J. Yong, W. Lee, and S.-G. Kim, "A high fill-factor infrared bolometer using micromachined multilevel electrothermal structures," *IEEE Trans. Elec. Dev.*, Vol. 46, pp. 1489-1491, 1999.

[3] C. Chen, X. Yi, J. Zhang, and X. Zhao, "Linear uncooled microbolometer array based on VOx thin films," *Infrared Physics & Tech.*, Vol. 42, pp. 87-90,

2001.

[4] S. Eminoglu, D. S. Tezcan, M. Y. Tanrikulu, and T. Akin, "Low-cost uncooled infrared detectors in CMOS process," *Sensors & Actuators*, Vol. A109, pp. 102-113, 2003.

[5] R. A. Wood, "High performance infrared thermal imaging with monolithic silicon focal planes operating at room temperature," *in Proceedings of IEEE IEDM*, 1993.

[6] S. Han, C. Chun, C. Han, and S. Park, "Coupled physics analyses of VO_x-based, three-level microbolomter," *Electron. Mater. Lett.*, Vol. 5, pp. 63-65, 2009.

[7] J. A. Potkay, G. R. Lambertus, R. D. Sacks, and K. D. Wise, "A low-power pressure- and temperature-programmable GC column," *in Proceedings of Solid-State Sensor, Actuator and Microsystem Workshop*, 2006.

[8] B. E. Cole, R. E. Higashi, and R. A. Wood, "Monolithic arrays of micromachined pixels for infrared applications," *in Proceedings of IEEE IEDM*, 1998.

[9] P. W. Kruse and D. D. Skatrud, *Uncooled infrared imaging arrays and systems*: Academic Press, 1997.

[10] H. H. Jones, S. Aslam, and B. Lakew, "Bolometer simulation using SPICE," *in Proceedings of Int. Thermal Detectors Workshop*, 2004.

[11] D. Yvon and V. Sushkov, "Low Noise Cryogenic Electronics: Preamplifier configurations with feedback on the bolometer," *IEEE Trans. Nuclear Sci.*, Vol. 47, pp. 428-437, 2000.

[12] J. Shie, Y. Chen, M. Ou-Yang, and B. Chou, "Characterization and modeling of metal-film microbolometer," *J. MEMS*, Vol. 5, pp. 298-306, 1996.

[13] P. Capper and C. T. Elliott, *Infrared detectors and emitters: materials and devices*, Kluwer Academic Publishers, 2001.

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