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Material selection for microelectronic heat sinks: An application of the Ashby approach

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ABSTRACT

This paper focuses on optimal materials selection for microelectronic heat sinks to maximize the thermal, mechanical and electronic response based on electro-thermal heat transfer analysis using the Ashby approach. In this work, material indices have been developed for a number of properties of heat sinks supported by materials selection tables/graphs. It is found that aluminum based alloys/metals perform better than other available materials for microelectronic heat sinks.

1. Introduction

Heat sinks are the most common and cost-effective hardware employed for the thermal management of microelectronic circuits and microelectromechanical systems (MEMS) devices. Heat sinks find wide applications in microelectronics and have become almost essential to modern integrated circuits like microprocessors, digital signal processors (DSP), graphics processing units, and more [1]. In common use, it is a metal object brought into contact with an electronic component's hot surface—though in most cases, a thin thermal interface material mediates between the two surfaces. Microprocessors and power handling semiconductors are examples of electronics that need a heat sink to reduce their temperature through increased thermal mass and heat dissipation (primarily by conduction and convection and to a lesser extent by radiation).

Materials selection for engineering design needs a clear understanding of the functional requirements for each individual component and various important criteria/factors need to be considered. The selection of materials for microelectromechanical systems (MEMS) is complicated by the highly integrated multifunctional roles of the components. The conventional set of MEMS materials like silicon compounds, metals and alloys, ceramics/glasses, polymers and composites [1,2] although compatible with existing micromachining techniques, are not an optimal choice for the maximum performance of devices. The growing interest in developing microelectronic heat sinks on various electronic devices presents an opportunity to expand the present set of MEMS materials to improve the functionality of such devices by optimal material selection.

The existence of several techniques, mathematical and physical models to integrate large MEMS material sets into microsystem design has provided an impetus in adopting a rational approach for material selection in electronic/MEMS component design and fabrication [2–10]. As a step towards such an approach, we focus on the material selection for heat sinks which are widely used in microelectronic circuits for optimum thermal management [11]. The key performance indices for microelectronic heat sinks are thermal conductivity (λ), electrical resistivity (ρ_e), thermal expansion (α) and Young's Modulus (E) [5]. This paper discusses a strategy for selecting suitable materials for heat sinks based on electro-thermal heat transfer analysis compatible with Ashby approach in order to improve the device performance.

The paper is organized as follows: Section 2 discusses the materials and their properties used in MEMS devices. Section 3 reviews the Ashby methodology. Section 4 is devoted to heat sinks and equations involved in heat transfer, while Section 5 involves application of Ashby method for material selection in microelectronic heat sinks. We discuss our results and conclusions in Section 6.

2. Materials and properties for MEMS devices

The present day technologies involving processing techniques such as bulk-micromachining, surface micromachining and soft

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lithography, have made it possible to introduce, shape, and integrate a large number of engineering materials into MEMS elements [2,3]. These materials are traditionally grouped into four classes: metals and alloys, glasses and ceramic, polymers and elastomers, and composites.

The properties of materials commonly required in mechanical design are the Young's Modulus (E), density (ρ), Poisson's ratio (ν), fracture strength (σ_F), yield strength (σ_Y), fracture toughness (K_{IC}), coefficient of thermal expansion (α), specific heat capacity (C_p), loss coefficient (η), and residual stress (σ_R) [3]. Using the method of Ashby, the designers have to consider the above material properties to optimize device performance and reliability in microsystems design. Certain electrical properties like resistivity and conductivity are also considered for electrical components in such designs.

Compared to the properties of macroscale ("bulk") structures, the properties of microscale structures can potentially be functions of the length scale as well as the details of processing techniques employed. However, it is possible to quantitatively relate micromechanical properties to bulk properties in many cases by focusing on structures with minimum feature sizes greater than 1 μm [3].

Some of the properties whose physical origins scale down to the atomic level and which can be included in micromechanical (>1 μm) and bulk structures include the Young's Modulus, density, Poisson's ratio, coefficient of linear expansion, and the specific heat. Sharpe [8] have tabulated initial design values based on an extensive survey of such measurements whose values are listed in Table 1 along with nominal bulk values tabulated by Ashby and Jones [12]. Thus, $0.8E_{bulk} < E_{\mu} < E_{bulk}$ can be concluded where the subscript 'μ' indicates microscale. Therefore, for the initial stages of micromechanical design, bulk values of these properties can be used. Based on this, Table 2 summarizes the initial design values for various material properties.

Table 1
Comparison of bulk and microscale properties.

Materials	E_{bulk} (GPa) Ref. [12]	E_{μ} (GPa) Ref. [8]	$\sigma_{F,bulk}$ (MPa) Ref. [12]	$\sigma_{F,\mu}$ (MPa) Ref. [8]
Aluminum	69	70	200	150
Copper	124	120	400	350
Gold	82	70	220	300
Nickel	214	180	400	500
Ni–Fe alloy	130–234	120	400–2000	1600
Diamond-like carbon	700–1000	800	8000–10,000	8000
Poly Si	130–180	160	2000–4000	1200–3000
Single crystal Si	130–180	125–180	2000–4000	>1000
SiC	430–445	400	4000–10,000	–
Silicon nitride	280–310	250	5000–8000	6000
Silicon oxide	50–80	70	800–1100	1000

Table 2
Recommended initial design values of material properties.

Property	Recommendation
Density, ρ (kg m^{-3})	$\rho_{\mu} = \rho_{bulk}$ (approx)
Young's Modulus, E (GPa)	$0.8E_{bulk} \leqslant E_{\mu} \leqslant E_{bulk}$
Poisson's ratio, ν (–)	0.25
Fracture strength, σ_F (MPa)	$\sigma_{F,\mu} = \sigma_{F,bulk}$ (approx)
Linear expansion coefficient, α (K^{-1})	$\alpha_{\mu} = \alpha_{bulk}$ (approx)
Specific heat, C_p (J kg^{-1} K^{-1})	$C_{p,\mu} = C_{p,bulk}$
Intrinsic loss coefficient, η_i	$10^{-2} < \eta_i$ (polymers) $10^{-5} < \eta_i$ (metals) $10^{-7} < \eta_i < 10^{-4}$ (ceramics)
Residual stress, σ_R (MPa)	-1 GPa $< \sigma_R < 1$ GPa

3. Materials selection: the Ashby method

The Ashby method sets out the basic procedure for selection, establishing the link between the material and function as shown in Fig. 1. A material has several attributes like density, strength, Young's Modulus, cost, resistance to corrosion, etc. [5]. A design demands a certain profile of these and the following tasks have been suggested: (i) identifying the desired attribute profile and (ii) comparing it with those of real engineering materials to find the best match. The selection strategy of materials involves four main steps, comprising of translation, screening, ranking and supporting information [5,13]. These steps as illustrated in Fig. 2, can be interlinked to select the best suitable materials in microsystem design.

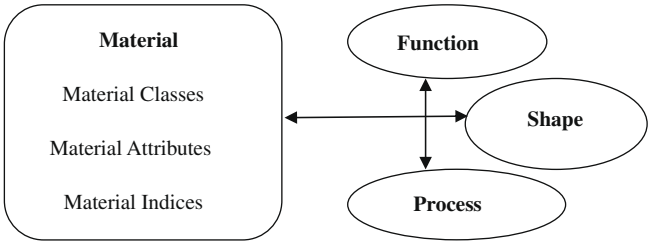

Fig. 1. Basic process linkage for material selection.

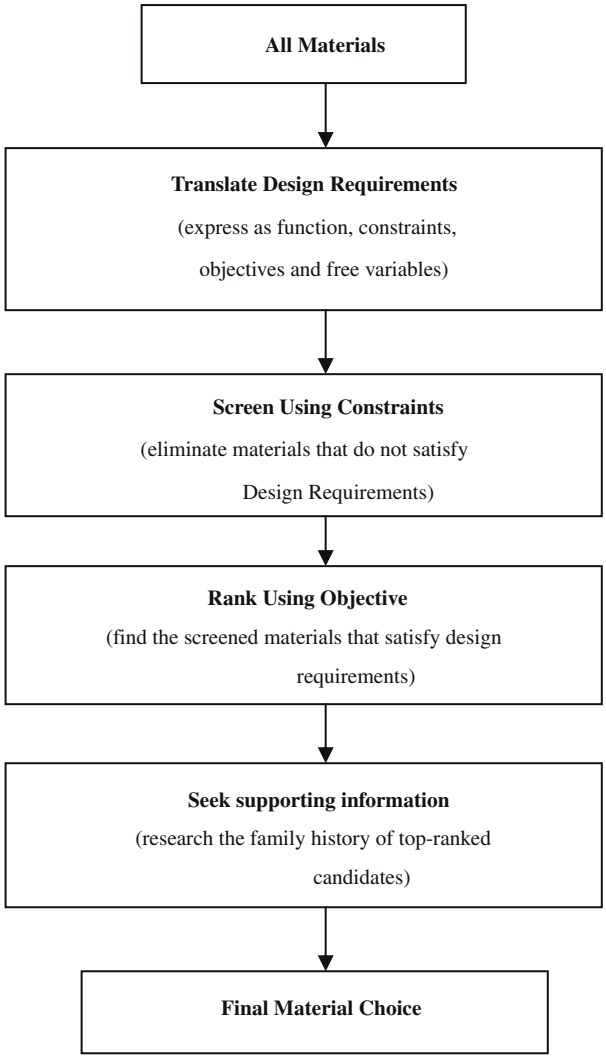

Fig. 2. Steps involved in materials selection.