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Short communication

Materials selection for thin films for radio frequency microelectromechanical systems

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Abstract

Materials selection is an important subject in microtechnology. The methodology developed by Ashby is used here. It is shown that it can be applied easily to microelectromechanical systems (MEMS). Firstly, a selection concerning a minimization of intrinsic residual stresses for thin films deposited by evaporation process is presented. Secondly, the selection of materials to serve in the design of the bridge of a MEMS-RF switch and a MEMS-RF varicap (variable capacitor) is considered.

1. Introduction

Thin films are the building blocks of most types of microsystems, like microelectromechanical systems (MEMS). During the deposition of thin films, residual stresses generally appear. These stresses can influence the reliability of the deposited systems due to fatigue, aging effects or debonding. Therefore this aspect is of crucial importance for metallizations of microelectronic devices and MEMS.

Residual stresses depend on many parameters, like the nature of the materials involved, the deposition process, the thermal history of the systems. It is then obvious that one has to carefully select materials, in order to reduce residual stresses.

At the same time, the devices have to fulfil various conditions, in order to work correctly. Hence the materials selection must also take the function of the system into account.

In order to select the correct materials, an appropriate methodology has to be used. Here, we choose the methodology proposed by Ashby [1]. After a brief description of the method, it is first applied to the selection of materials with minimum residual intrinsic stresses. Then, we apply the same methodology to two MEMS, namely the MEMS-RF switch and varicap [2–4]. The first one is a switch which just describes an ON/OFF state and the other is a variable capacitor application.

It is worth to mention that any materials selection relies on an appropriate database. Our database is developed by our department for the Oofelie's software developed by Open-engineering firm [5]. It contains various properties (mechanical, thermal, electrical, optical) of about 167 materials.

2. Ashby's methodology

The design of a structural element is specified by three parameters groups: the functional requirements F, the geometric parameters G and the materials properties M. The performance of the element p is described by the following relation [1]:

$$p = f(F, G, M) \tag{1}$$

The optimum design is the selection of the material and geometry which maximize or minimize p. If the function describing p is assumed to be separable then p can be written as [1]

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$$p = f_1(F)f_2(G)f_3(M) \tag{2}$$

This implies that the optimum choice of the material becomes independent of the other details of the design F and G. $f_3(M)$ is called the index material. In the following, three different materials index are defined.

3. Materials selection for minimizing residual intrinsic stress

It is well known that the total residual stress is a sum of three components: intrinsic, thermal and external ones [6]. The intrinsic component appears during the deposition process itself. It is due to a thermal shock between the evaporated material and the substrate when the vapor condenses on the substrate. The thermal component is due to the cooling phase of the deposited layer on the substrate. And the external component is due to all external stresses acting on the system films/substrate due, for example, to impurities and oxidation.

Here, only intrinsic residual stresses are considered because this component only implies materials properties of the deposited layer.

For an evaporation process, the intrinsic residual stress is given by [7]

$$\sigma_{\text{initial\_intrinsic}} = \beta\left(\frac{E}{1-\nu}\right)\alpha(T_{\text{melting}} - T_{\text{substrate}}) \tag{3}$$

$$\beta \approx \kappa^{-1} \tag{4}$$

The factor β is a reducing factor introduced to take into account the fact that the heat transfer is not instantaneous. The materials dependence of the reducing factor is the thermal conductivity of the deposited layer, κ. All the materials properties which appear in the initial residual stress are the biaxial young modulus $E/1-\nu$, the thermal expansion coefficient α, the melting temperature T_{melting} and the thermal conductivity of the deposited layer κ.

For residual stresses, the index material is then IM_1

$$\text{IM}_1 = \alpha E T_{\text{melting}}/[\kappa(1-\nu)] \tag{5}$$

For minimizing the residual stress, we minimize IM_1. From our database [5], we conclude that, among our 167 materials, the best ones are rubidium, boron nitride, potassium, silver, arsenic, carbon, magnesium, gold, copper and aluminium.

In order to visualize the results, an alternative way is to rewrite the condition for minimizing IM_1, as to plot a graph $\alpha E T_{\text{melting}}/(1-\nu)$ versus κ. The red line in Fig. 1 (refer online version for colour) is there to guide the eye in the selection of the ten materials which have the lowest $\alpha E T_{\text{melting}}/(1-\nu)$ value and the highest κ value.

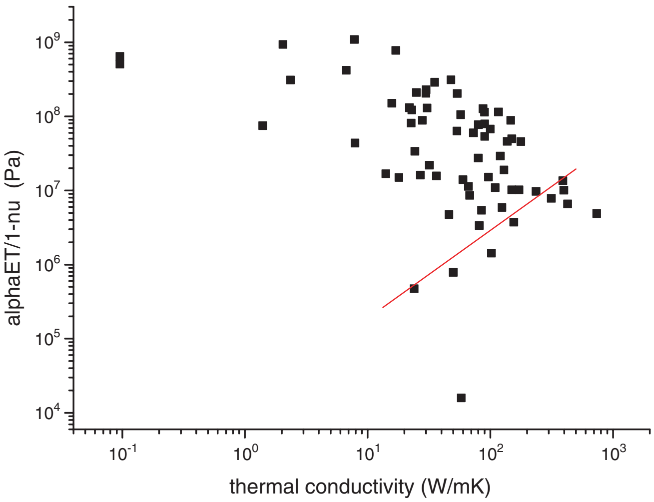

Fig. 1. The low right corner of the graph exhibited materials with small intrinsic residual stress.

4. MEMS-RF, how does it works?

Let us now address the particular case of the MEMS-RF. The simplest design of the considered MEMS-RF applications is to consider that it consists of two parallel conductivities plates forming a capacitor with an effective overlap area A and separated by a gap distance s. The top plate is mobile and the bottom plate is fixed. So when applying a DC voltage, V, between the plates, an electrostatic force appears. When V reaches a value called pull-in voltage, $V_{\text{pull-in}}$, the top plate collapses on the bottom plate. This is unwanted for a varicap but this is the normal job of a switch. The pull-in voltage is given by the following equation:

$$V_{\text{pull-in}} = \sqrt{\frac{8Es^3}{27\varepsilon A}} \tag{6}$$

Considering the materials dependent properties of the pull-in voltage, it turns out that

$$V_{\text{pull-in}} \approx \sqrt{E} \tag{7}$$

So pull-in voltage is proportional to the square root of the young modulus.

Another important parameter for MEMS-RF applications is the quality factor which is defined as the ratio between reactance and resistance $Q = R^{-1}\sqrt{L/C}$ with L the inductance and C the capacitance. Assuming a constant value for reactance, the quality factor is only inversely proportional to the resistance. The resistance is calculated by the Pouillet's law. Then $Q \approx \rho^{-1}$ where ρ is the electrical resistivity of the material.

5. Materials selection for a bridge of a MEMS-RF switch

In this kind of MEMS a low pull-in voltage and a high quality factor are needed [2,3]. The following index material IM_2 is defined:

$$\text{IM}_2 = \sqrt{E}/\rho^{-1} \tag{8}$$

So low IM_2 values are required. Generally speaking, the top plates of MEMS-RF are made in aluminium. Other materials may be searched for. Materials exhibiting index material IM_2 values lower than aluminium are gold, copper, magnesium, calcium, sodium, silver, potassium and rubidium.

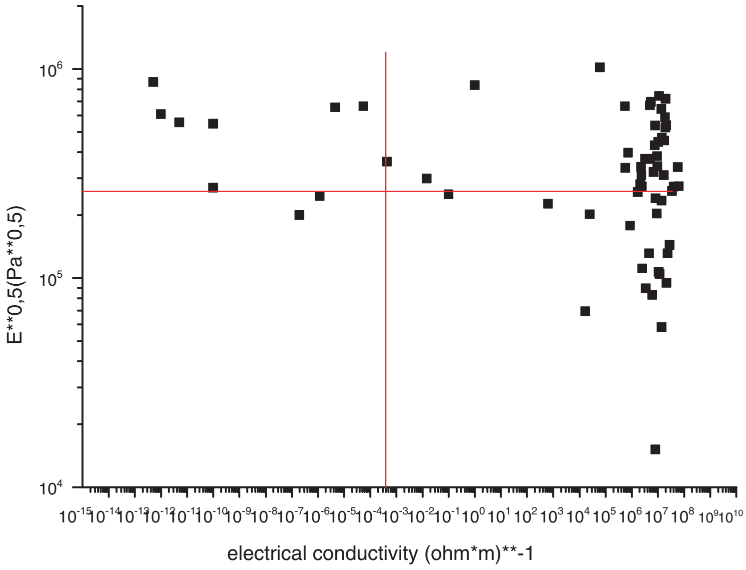

Fig. 2. The upper right corner of the graph exhibited materials with high pull-in voltage and high quality factor. The lower right corner exhibited materials with low pull-in voltage and high quality factor.

To represent the materials selection, $\sqrt{E}$ versus electrical conductivity ρ^{-1} is plotted (Fig. 2). A vertical line passing by Si material point is drawn to distinguish between insulators and conductors. An horizontal line is also drawn, passing by Al to distinguish materials with pull-in voltage higher than Al and materials with pull-in voltage lower than Al. The interesting part of the graph for a switch application is the lower right corner in Fig. 2. This part contains materials with low pull-in voltage and high quality factor.

So if we take into account our first selection concerning the residual stresses and the present selection for MEMS-RF switch we obtain the following materials: Au, Cu, Mg, Ag, K and Rb.

6. Materials selection for a bridge of a MEMS-RF varicap

In this kind of MEMS, a high pull-in voltage and a high quality factor are needed [2,4]. High pull-in voltage is necessary to obtain a large available capacitance domain. The following index material IM_3 is defined:

$$IM_3 = \sqrt{E}\rho^{-1} \tag{9}$$

So high IM_3 values are required. Materials exhibiting index material IM_3 value higher than aluminium are: copper, silver, iridium, gold, rhodium, tungsten and molybdenum.

To represent the materials selection, Fig. 2 is also used. But the interesting part of the graph for a varicap application is the upper right corner in Fig. 2. This part contains materials with high pull-in voltage and high quality factor.

So if we take into account our first selection concerning the residual stresses and the present selection for MEMS-RF varicap we obtain the following materials: Cu, Ag and Au.

7. Remark

We note that in our three materials selection (see Tables 1–3). We have some highly reactive materials with air oxygen like Mg, K, Rb, Ca and Na. So for MEMS applications it is preferable to delete these materials from our three selections [8].

Table 1
Index material IM_1 values for the 10 selected materials

Material	Index material (Pa K m/W)
Al	4.10×10^4
Cu	2.54×10^4
Au	2.48×10^4
Mg	2.39×10^4
C	1.96×10^4
As	1.57×10^4
Ag	1.53×10^4
K	1.39×10^4
BN	6.57×10^3
Rb	2.73×10^2

Table 2
Index material IM_2 values for the selected materials

Material	Index material ($Pa^{1/2}\,\Omega$ m)
Al	7.35×10^{-3}
Au	6.68×10^{-3}
Cu	5.83×10^{-3}
Mg	5.64×10^{-3}
Ca	5.18×10^{-3}
Na	4.51×10^{-3}
Ag	4.43×10^{-3}
K	4.19×10^{-3}
Rb	1.90×10^{-3}

Table 3
Index material IM_3 values for the selected materials

Material	Index material ($Pa^{1/2}\,\Omega^{-1}\,m^{-1}$)
Cu	1.97×10^{13}
Ag	1.71×10^{13}
Ir	1.40×10^{13}
Au	1.12×10^{13}
Rh	1.12×10^{13}
W	1.10×10^{13}
Mo	1.01×10^{13}
Al	9.25×10^{12}

8. Conclusions

In conclusion, materials exhibiting minimal intrinsic residual stress, low pull-in voltage and high quality factor are: Au, Cu, Mg, Ag, K and Rb. We reject highly reactive materials Mg, K and Rb. So Au, Cu and Ag could be used in MEMS-RF switch applications.

Materials exhibiting minimal intrinsic residual stress, high pull-in voltage and high quality factor are: Cu, Ag and Au. It could be used in MEMS-RF varicap applications.

Thus Cu, Ag and Au can be used in switch or varicap MEMS-RF application. This could be useful to know it for fabrication process, to standardize the fabrication process for MEMS-RF applications. It will reduce fabrication cost in building one kind of MEMS-RF with two available applications. So these materials are better than aluminium for these kinds of applications.

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