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COMPUTER SIMULATION OF THERMO-MECHANICAL STRESSES IN COMPONENTS OF POWER SEMICONDUCTOR DEVICES

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ABSTRACT

The article presents the results of computer simulation of thermo-mechanical stresses and deformations in the components of power semiconductor devices (PSD) consisting of electrically active silicon crystal and molybdenum temperature compensator put together with the use of two technologies: the technology of low-temperature sintering with an intermediate silver paste layer and the technology of welding with layer of aluminum alloy. The calculations were carried out by the method of finite element analysis using ANSYS software. Results of computer simulation demonstrate that the level of mechanical stresses in the components of PSD with a layer containing sintered silver paste is much lower than in the components with a layer containing aluminum alloy. Based on calculations it can be concluded that the maximum thermo-mechanical stresses during fabrication of these components occur at their periphery in the ring region, where the width is approximately equal to the thickness of PSD component.

Keywords: power semiconductor devices, silicon on molybdenum structure, thermo-mechanical stresses, computer simulation.

1. INTRODUCTION

The key electrical parameters and reliability of power semiconductor devices (PSD) is largely determined by the quality of connection between an electrically active semiconductor component and a temperature compensator. Inter-component connections in the PSD must have a minimum electrical and thermal resistance, low inductance, the capability to quickly remove power loss occurring during operation of the device, ensure the mechanical performance of the devices under a wide range of temperatures and cyclic loads of power.

Traditionally, to join the components in a powerful PSD, technology of alloying by high temperature solders is used, such as Al-Si alloy [1]. More promising is the technology when components are joined by low-temperature sintering (Low Temperature Joint Technique - LTJT) [2-4]. The LTJT is a technological way of joining electrically active silicon component with temperature compensator by sintering a special silver-containing paste, when exposed to temperature and pressure. It is herewith important to take into account the thermo-mechanical stresses arising in the process of fabrication of multi-layer inter-component connections.

There is a number of papers concerned with the study of thermo-mechanical stresses in multilayered structures, including semi-conductive ones, e.g. [5-12]. In particular, in [6] the authors analytically calculated the temperature dependence of the curvature radius of the three-layer metal system, being deformed when heated or cooled.

The purpose of this paper was to study by means of numerical simulation, thermo-mechanical stresses and deformations that occur in the system, consisting of electrically active silicon component and molybdenum temperature compensator, joined together by traditional technology of a eutectic Al-Si alloy or LTJT with silver paste. This system is conventionally called “silicon on molybdenum” structure (SoM). The physical form of real SoM structures, on the basis of which the joint-stock company «ELECTROVIPRYAMITEL» (Saransk, Russia) manufacture powerful thyristors is presented in Figure-1.

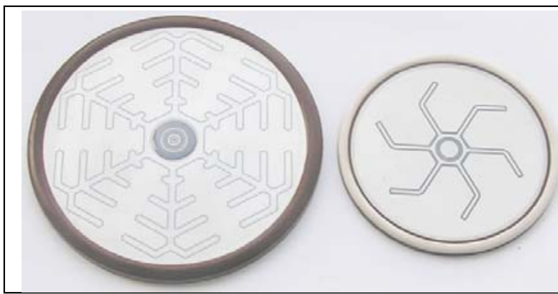

Figure-1. Physical form of SoM structures.

2. METHODOLOGY OF STUDY

For the numerical simulation we used ANSYS software. The calculations were performed by employing a finite element method.

The simulated SoM structure with diameter of 56 mm (Figure-2) consisted of a silicon disk 1, thickness - 1.9 mm and the molybdenum disk 3, thickness - 2.1 mm, firmly joined together by the intermediate layer 2.

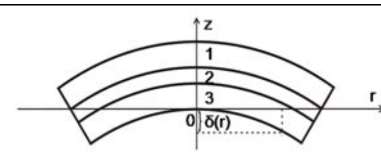

Figure-2. SoM structure diagramme: 1 - Silicon disk, 2 - joining layer, 3 - Molibdenum disk, δ –deflection of structure.

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The composition, thickness and physical characteristics of the joining layer 2 varied in the course of calculations.

In modeling process was used the values of the physical characteristics of layer materials in SoM structures (table-1) and their temperature dependence [13, 14].

Table-1. Physical characteristics of layer materials in SoM structures (T=300 K).

Material	Modulus of elasticity, GPa	Poisson ratio	Coefficient of thermal expansion, 10^{-6} K^{-1}
Si	170	0.22	2.6
Mo	329	0.37	4.8
Ag	83	0.37	18.9
Al-Si (4032)	78	0.34	19.5

3. RESULTS OF COMPUTER SIMULATION

Figure-3 shows the results of computer simulation for the distribution of equivalent mechanical stresses in a SoM structure with an intermediate layer of 4032 Al-Si alloy with thickness of 40 μm (a) and the sintered silver paste layer of the same thickness (b). These stresses occur when cooling SoM structure from the temperature of joining process (577 °C for Al-Si alloy and 250 °C for LTJT) to room temperature (20 °C).

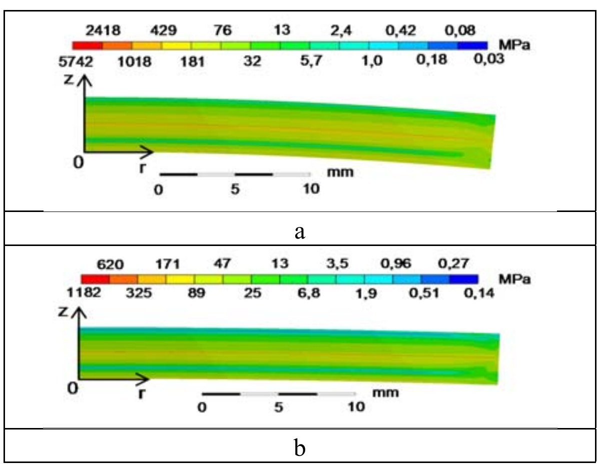

Figure-3. Distribution of equivalent mechanical stresses in a SoM structure with various joining layers: a – Al-Si alloy, b – Ag.

Figure-4 shows the simulation results of the stress distribution in the SoM structure in the direction to normal surface at various distances from the axis of the structure.

It ensues from Figure-4 that the absolute values of stresses in SoM structure with a joining layer based on Al-Si alloy is much higher than the corresponding stress values for the system with a sintered silver paste layer.

Of special interest are resultant significant mechanical stresses in the intermediate layer at the periphery of the structure. Such high local mechanical stresses may lead to the appearance of defects in Si structure affecting its electro-physical properties.

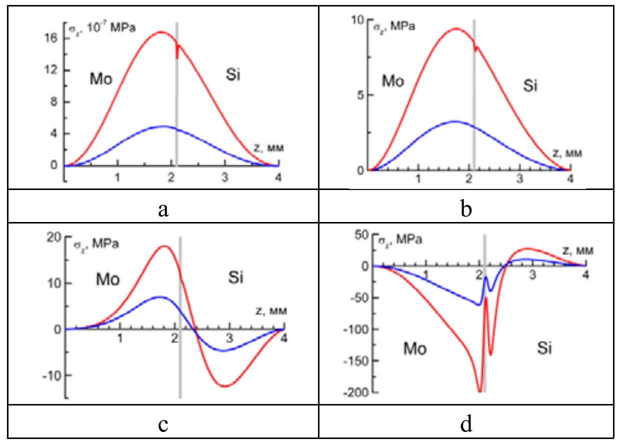

Figure-4. Distribution of stresses in SoM structure in the direction to normal surface at various distances from the axis: a – 10 mm; b – 25 mm; c – 27 mm; d – 27,9 mm. Material of joining layer: — Al-Si alloy (40 mkm), — Ag (40 mkm).

Figure-5 shows the results of simulation of the radial dependence of stresses in SoM periphery area with regard to different thicknesses of structure layers.

This figure illustrates that mechanical stresses concentrate in the peripheral ring region of SoM structure, and are significantly higher than the stresses in the rest of the structure. The linear size of this area is almost equal to the thickness of SoM structure.

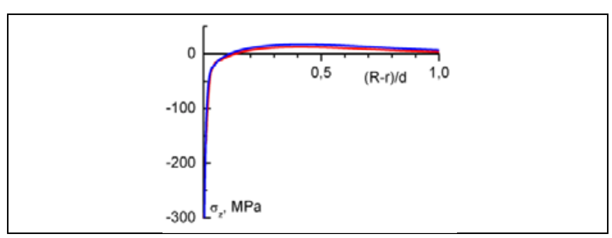

Figure-5. Distribution of mechanical stresses on the boundary Silicon - joining layer along the radius *r* of SoM structure with layer thicknesses: Si – 1,9 mm, Ag – 0,04 mm, Mo – 2,1 mm (—) и Si – 3,8 mm, Ag – 0,08 mm, Mo – 4,2 мм (—). *R, d* – radius, structure thickness.

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Figure-6 presents the simulation results for the surface shape of SoM structure with respect to different thicknesses and materials of joining layers. From the results of numerical calculations it follows that the thickness of structures in the process of cooling from the temperature of joining process to room temperature is almost constant except for the peripheral region.

Figure-7 shows the simulation results pertaining to dependence of deflection of SoM structures on the thickness and the material of the joining layer. The same figure shows the results of calculation of the deflection according to the formula given in [6], without temperature dependence of the physical characteristics of layer materials. It ensues from the diagrams that the absolute value of the structures' deflection decreases with the increase in layer thickness. Whereas with the width of joining layer of 40 mkm, the deflection of SoM structures produced by LTJT is 2.5 times less than deflection of SoM resulted from Al-Si alloy.

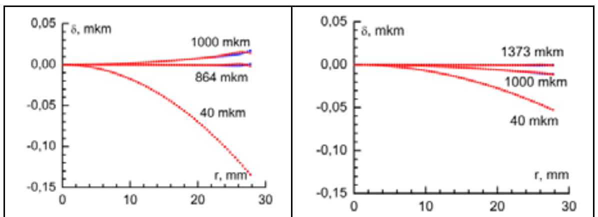

Figure-6. Results of simulation of exterior surface profile of SoM structure with joining layers of various composition and width: a – Al-Si alloy, b – Ag. Surface of Si (—), surface of Mo (—).

It is important to note that at certain values of the thickness of the joining layer (864 mkm for Al-Si alloy and 1373 mkm for Ag) deflection of SoM structure tends to zero. In this case the surface of Silicon and Molybdenum become almost flat. With further increase in the thickness of the intermediate layer deflection changes sign and grows almost linearly.

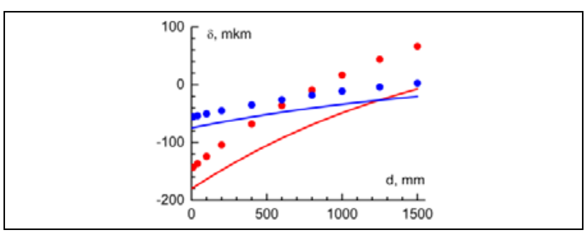

Figure-7. Dependence of SoM structure deflection on thickness of joining layer in Al-Si alloy (—) and Ag (—). Solid lines are results of analytical calculation in accordance with [6] (without temperature dependence of the physical characteristics of layer materials).

The simulation results also showed that related to thermo-mechanical stresses deflection of SoM structures depends not only on the type of material and thickness of the joining layer, but also on the thickness of the joined components of the structure. Figure-8 shows the dependence of SoM structure deflection on the thickness of molybdenum compensator with regard to structures with various material of the joining layer.

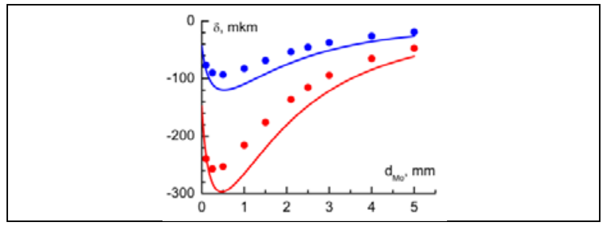

Figure-8. Dependence of SoM structures deflection with joining layers on the thickness of molybdenum compensator. — Al-Si alloy (40 mkm), — Ag (40 mkm). Solid lines are results of analytical calculation in accordance with [6] (without temperature dependence of the physical characteristics of layer materials).

The simulation results also suggest that using compensators with the width of over 4 mm in SoM structure only slightly reduces the deflection of the structure.

When forming SoM structures using the technology of LTJT the joining layer with sintered silver paste has pores [15, 16]. Porosity can alter the mechanical characteristics of the layer, for example, to reduce the Modulus of Elasticity. Figure 9 shows the simulation results pertaining to the dependence of SoM structure deflection on Modulus of Elasticity. Following this Figure one can clearly see that the reduction of the Modulus of Elasticity of the material of the joining layer in 2 times increases the deflection of the structure only by 2.5% (Al-Si), and by 1.8% (Ag). Based on this we can conclude that the porosity of the joining layer does not significantly affect the deflection of SoM structures.

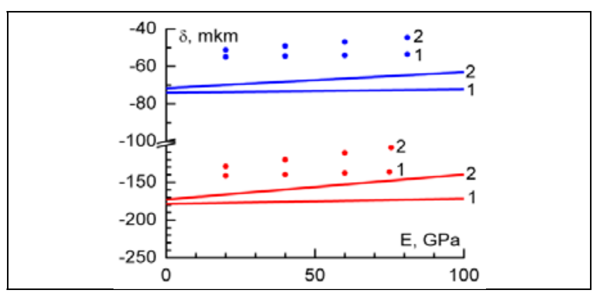

Figure-9. Dependence of SoM structures deflection on Modulus of Elasticity and thickness of joining layer Al-Si alloy (—) and Ag (—). The thickness of joining layer: 1 – 40 mkm, 2 – 200 mkm. Solid lines are results of analytical calculation in accordance with [6] (without temperature dependence of the physical characteristics of layer materials).

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4. CONCLUSIONS

Therefore, in the present paper, we have carried out a numerical calculation of mechanical stresses and deformations in SoM structure consisting of electrically active silicon wafer and molybdenum compensator, joined together by a silver paste layer as per LTJT technology or by wielding with Al-Si alloy.

The results of computer simulation suggest that the absolute values of the deflection and stresses in SoM structure with a joining layer of aluminum alloy increase significantly the corresponding deflection and stress values for the system with sintered silver paste layer. Calculations also indicate that in fabrication of SoM structures the highest thermo-mechanical stresses occur at the periphery of the structure in the area where the linear sizes are almost equal to the thickness of SoM structure. Such high local mechanical stresses can cause the appearance of defects in Si structure affecting its electro-physical properties.

The temperature dependence of physical characteristics of materials in SoM structures has a rather strong impact on the deflection of structures; a particularly strong influence on the deflection can be attributed to the dependence of the modulus of elasticity on the temperature.

The porosity of a joining layer has no significant effect on the deflection of SoM structures.

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REFERENCES

[1] W.H. Tarn. 1971. Process for soldering silicon wafers to contacts. Patent US 3555669 A, Patented January 19.

[2] J. Fellenger, W. Baumgartner. 1989. Befesting eines electronischen Bauelements auf Substract und ein Verfahren zur Herstellung der Befestigung. Patentschrift DE 3414065 C2, Deutsches Patentamt.

[3] H. Schwarzbauer. 1991. Europäische Patentschrift EP 0 242 626 B1, Europäisches Patentamt.

[4] H. Schwarzbauer, R. Kuhnert. 1991. Novel large area joining technique for improved power device performance. IEEE Trans. Ind. Appl. 27(1): 93-95.

[5] S.P. Timoshenko. 1925. Analysis of bi-metal thermostats. J. Optical Soc. of America and Reviue of Scientific Instruments. 11(3): 233-255.

[6] M. Vasudevan, W. Johnson. 1961. On multi-metal thermostats. Appl. sci. Res. Section B. 9: 420-430.

[7] E. Suhir. 1989. Interfacial stresses in bimetal thermostats. Journal of Applied Mechanics. 56: 595-600.

[8] H.W. Ng, Z. Gan. 2005. A finite element analysis technique for predicting as-sprayed residual stresses generated by the plasma spray coating process. Finite Elements in Analysis and Design. 41: 1235-1254.

[9] A. Carplnteri, M. Paggi. 2008. Thermo-elastic mismatch in nonhomogeneous beams. J. Eng. Math. 61: 371-384.

[10] T. Lackner. 2004. Determination of Axisymmetric Elastic Constants in Anisotropic Silicon for a Thyristor Tablet. Journal of Electronic Materials. 18(1).

[11] Y. Wen, C. Basaran. 2004. An analytical model for thermal stress analysis of multi-layered microelectronic packaging. Mechanics of Materials. 36: 369-385.

[12] Z.Q. Jiang, Y. Huang, A. Chandra. 1997. Thermal stresses in layered electronic assemblies. Journal of Electronic Packaging. 119: 127-132.

[13] Database of engineering materials. Available: http: //www.matweb.com

[14] J. Gilbert Kaufman. 2006. Properties of Aluminum Alloys: Tensile, Creep and Fatigue Data at High and Low Temperatures. Published by ASM International.

[15] C. Mertens.2004. Die Niedertemperaturverbindungste chnik in der Leistungselektronik. Seesen: VDI Verlag.

[16] K.N. Nishchev, M.I. Novopoltsev, K.V. Savrasov, V.P. Mishkin, V.V. Eliseev, V.A. Martynenko, A.V. Grishanin. 2015. Investigation of the process low-temperature sintering of silver-pastes by scanning electron microscopy. Applied Physics. 2015(3): 10-14.