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Effect of Stress on the Dielectric Constant of Alumina

The relative dielectric constant (10 kHz) of alumina was found to increase reversibly (by up to 13%) with compressive stress (up to 18 MPa). The effect of stress on the relative dielectric constant diminishes with increasing stress, such that it is almost absent when the stress exceeds ~7 MPa. *The relative dielectric constant is higher during loading than subsequent unloading.* [DOI: 10.1115/1.1939029]

Introduction

Alumina (aluminum oxide, Al_2O_3) is widely used for substrates in electronic packaging [1–5]. This is because of its dielectric behavior, thermal and chemical resistance, low thermal expansion and low cost. An important aspect of the dielectric behavior is the dielectric constant, which is usually expressed as the relative dielectric constant (κ, which is equal to 1 for the case of vacuum). In order to avoid a capacitive effect, which would cause a signal propagation delay, κ should be low.

Because of the heating experienced by an electronic package during use, thermal stresses are often encountered, particularly when there is a mismatch in the coefficient of thermal expansion (CTE) of adjoining materials in the package. The thermal stresses may cause warpage, interface degradation, and even debonding. They constitute one of the main causes of the reliability problem of electronics. In addition to thermal stresses, mechanical stresses can be encountered, because of vibrations and handling.

In spite of the common occurrence of stress in an electronic package, the effect of stress on κ of dielectric materials used in electronic packaging has not been previously addressed. This paper is thus focused on the effect of stress on κ of alumina.

The effect of stress on κ is associated with its effect on the electric polarization. It corresponds to the direct piezoelectric effect. This effect is large and well known for titanate and zirconate ceramics [6–12], however, it has not been reported for alumina. This effect is to be distinguished from the reverse piezoelectric effect (or electrostriction), which has been reported for alumina [13] and aluminum nitride [14].

Experimental Methods

The alumina used was a commercial substrate material containing 96 wt. % Al_2O_3, of size 25.4×25.4×0.6 mm. Dielectric constant measurement was performed by sandwiching an alumina substrate between copper disks of 12.3 mm diameter, at a pressure of 1.68 kPa. Prior to sandwiching, the copper disks had been mechanically polished on both sides by using alumina particles of size 0.25 μm. The copper disks served as electrical contacts.

The real and imaginary parts of the impedance were measured along the thickness of the specimen using the two-probe method and a Resistance–Inductance Capacitance Meter (RLC) meter (QuadTech 7600) at a fixed frequency (10 kHz). The magnitude of voltage applied across the thickness (0.6 mm) of a specimen was 1.000 V. Hence, the magnitude of the applied electric field was 1700 V/m. The resistance (real part of the impedance) and reactance (imaginary part of the impedance) were obtained from the impedance by assuming that they were in series connection. The capacitance was obtained from the reactance. To show that the quality of the electrical contacts was good, the measurement was also conducted when silver paint had been applied between each copper disk and the specimen.

During the impedance measurement, compressive stress was applied to the sandwich, so that the stress was parallel to the direction of impedance measurement. The stress (repeated loading at increasing stress amplitudes within the elastic regime of alumina) was provided by a hydraulic mechanical testing system (MTS Model 810, MTS Systems Corp., Marblehead, MA). The minimum compressive stress was 1.68 kPa.

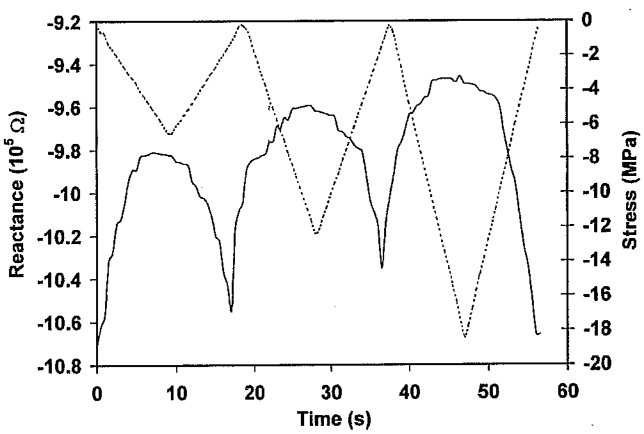

Fig. 1 Variation of the reactance with time (solid curve) and of the compressive stress with time (dashed curve) for alumina with silver paint at the electrical contacts

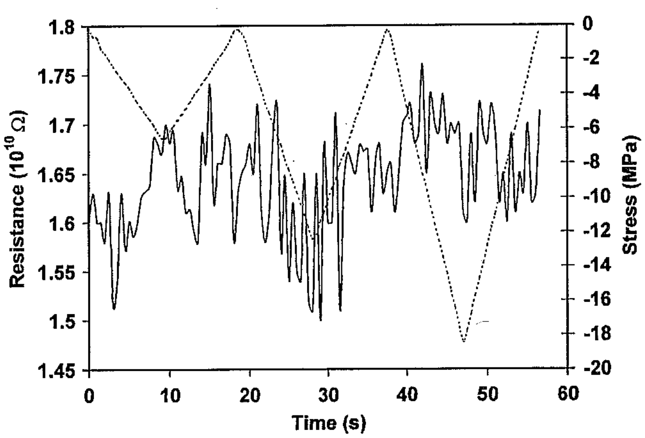

Fig. 2 Variation of the resistance with time (solid curve) and of the compressive stress with time (dashed curve) for alumina with silver paint at the electrical contacts

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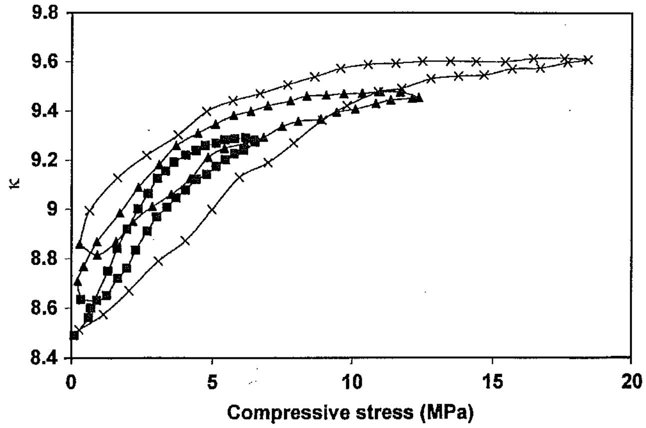

Fig. 3 Variation of the relative dielectric constant κ with the compressive stress during the three cycles of stress variation in Fig. 1. First cycle: ν; second cycle: σ; third cycle: 5. In each cycle, κ is higher during loading than subsequent unloading.

Results and Discussion

Figure 1 shows the reactance and applied stress (negative for compression) during repeated compressive loading of alumina with silver paint at the adjoining surfaces of the two copper disks. The magnitude of the reactance decreases (i.e., κ increases) upon loading, and the effect is quite reversible; the greater the stress amplitude, the greater the effect.

Figure 2 shows the corresponding plot for the resistance, which was obtained simultaneously with the reactance in Fig. 1. The resistance does not show any systematic variation with stress. Although the resistance is high compared to the reactance, it is less than that expected for alumina, because of the experimental limitation in the measurement of large resistances.

The absence of silver paint at the adjoining surfaces of the two copper disks results in data that are quite similar to Fig. 1. The similarity means that the interface between alumina and the copper disks does not contribute to causing the observed change in the reactance with stress. This further means that the effect is due to the alumina itself.

Figure 3 shows the variation of κ with stress during the three cycles of stress variation at increasing stress amplitudes in Fig. 1. The variation is reversible, but it exhibits hysteresis such that κ is higher during the stress increase than the subsequent stress decrease in the same cycle. The increase of κ with stress is not linear. The effect becomes less as the stress increases. At a compressive stress beyond $\sim$7 MPa, κ essentially does not change with stress. At the stress levels used in this work, the strain in the alumina is so small that its effect on the capacitance of the sandwich is negligible.

The change of κ with stress is up to 13% (Fig. 1). This effect is very small compared to that of titanate or zirconate ceramics, but it is of concern to the performance of electronics that use alumina as a dielectric material.

Conclusion

The relative dielectric constant (10 kHz) of alumina increases reversibly with the compressive stress. The increase is up to 13% for a stress of up to 18 MPa. The increase is nonlinear, such that κ essentially does not change with stress at stresses above $\sim$7 MPa. The increase is hysteretic such that κ is higher during loading than during subsequent unloading.

References

[1] Kulkarni, A. K., Upadhyaya, D. D., and Rao, S. V. K., 1982, "Studies on Development of Alumina Substrates," Transactions of the Indian Ceramic Society **41** (2), pp. 25–29.

[2] Yatsuka, H., Ishizaki, M., Takano, T., and Komizo, H., 1980, "Millimeter-Wave IC Components Using Fine Grained Alumina Substrate," IEEE Mtt-S Int Microwave Symp Digest No. 80CH1545-3 MTT, pp. 276–278.

[3] Frost, H. M., and Shalek, P. D., 1987, "High-Temperature Dielectric Measurements of High-Purity Alumina Ceramics," *Conf. Digest - 12th Int. Conf. Infrared and Millimeter Waves*, IEEE, New York, No. 87CH2490-1, pp. 228.

[4] Ueyama, T., Wada, H., and Uehara, H., 1988, "Influence of Alumina Contents and Firing Temperature on the Electrical Properties of Alumina Substrates," J. Jpn. Soc. Powder Powder Metall. **35**(8), pp. 793–798.

[5] Varma, H. K., Mani, T. V., Warrier, K. G. K., Damodaran, A. D., and Balachandran, U., 1994, "Sintering of Thin Sheets of Alumina Prepared by the Sol-Spray Technique," J. Mater. Sci. Lett. **13**(7), pp. 491–493.

[6] Xia, F., and Yao, X., 2001, "Role of PbO Content on the Dielectric and Piezoelectric Properties of PZN-Based Ceramics," J. Mater. Sci. **36**(1), pp. 247–253.

[7] Hosono, Y., Harada, K., Yamashita, Y., Dong, M., and Ye, Z.-G., 2000, "Growth, Electric and Thermal Properties of Lead Scandium Niobate-Lead Magnesium Niobate-Lead Titanate Ternary Single Crystals," Jpn. J. Appl. Phys., Part 1 **39**(9), pp. 5589–5592.

[8] Kim, G. B., and Choi, S. W., 2000, "Dielectric, Pyroelectric and Piezoelectric Properties of $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ Ceramics Modified With Ag_2O" Jpn. J. Appl. Phys., Part 1 **39**(9B), pp. 5552–5555.

[9] Alberta, E. F., Bhalla, A. S., and Adachi, M., 2000, "Temperature Dependence of the Piezoelectric and Dielectric Coefficients of Niobium-Doped $Pb(Sc_{1/2}Nb_{1/2})_{0.58}Ti_{0.42}O_3$ Ceramics," Ferroelectrics **242**(1-4), pp. 13–24.

[10] Yoon, K. H., and Lee, H. R., 2000, "Effect of Ba_2 Plus Substitution on Dielectric and Electric-Field-Induced Strain Properties of PMN-PZ-PT Ceramics," J. Am. Ceram. Soc. **83**(11), pp. 2693–2698.

[11] Rukmini, H. R., Choudhary, R. N. P., and Prabhakara, D. L., 2000, "Sintering Dependent Physical and Dielectric Properties of $Pb_{0.91}La_{0.09}Zr_{0.65}Ti_{0.35}O_3$ Ceramics," J. Mater. Sci. Lett. **19**(19), pp. 1705–1708.

[12] Cho, Y. S., Pilgrim, S. M., Giesche, H., and Bridger, K., 2000, "Dielectric and Electromechanical Properties of Chemically Modified PMN-PT-BT Ceramics," J. Am. Ceram. Soc. **83**(10), pp. 2473–2480.

[13] Sundar, V., and Newnham, R. E., 1996, "Converse Method Measurements of Electrostriction Coefficients in Low-K Dielectrics," Mater. Res. Bull. **31**(5), pp. 545–554.

[14] Valbin, L., Sevely, L., and Spirkovitch, S., 2000, "Low Temperature Piezoelectric Aluminum Nitride Thin Film," *Proc. SPIE–The Int. Society for Optical Engineering, Micromachining and Microfabrication Process Technology*, SPIE, Bellingham, WA, Vol. 4174, pp. 154–163.